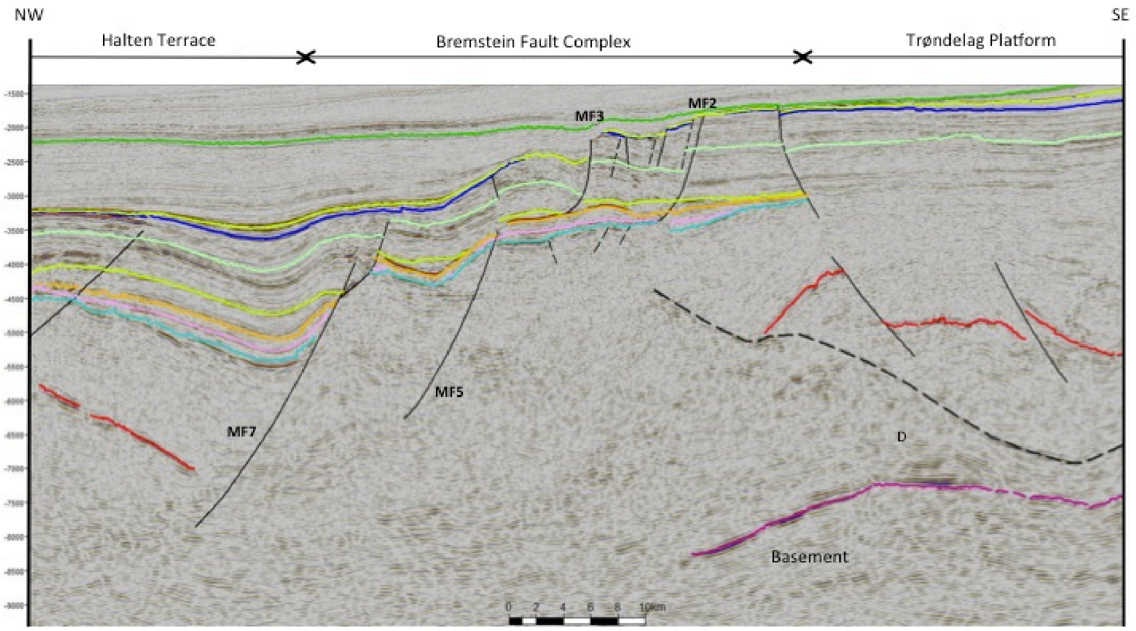
Master Thesis, Department of Geosciences

Structure and evolution of the Bremstein Fault Complex offshore Mid-Norway

Rikke Rørbakk Avaldsnes



UNIVERSITY OF OSLO
FACULTY OF MATHEMATICS AND NATURAL SCIENCES

Structure and evolution of the Bremstein Fault Complex offshore Mid-Norway

Rikke Rørbakk Avaldsnes

Master Thesis in Geosciences

Discipline: Petroleum Geology and Petroleum Geophysics

Department of Geosciences

Faculty of Mathematics and Natural Sciences

University of Oslo

June 2st, 2014

Tutor(s): **Jan Inge Faleide & Roy H. Gabrielsen**

This work is published digitally through DUO – Digitale Utgivelser ved UiO

http://www.duo.uio.no

It is also catalogued in BIBSYS (http://www.bibsys.no/english)

Preface

This master thesis constitutes the completion of the two year master program in Petroleum Geology and Petroleum Geophysics at the Department of Geosciences, University of Oslo.

Acknowledgements

I would like to thank my supervisors, Professor Jan Inge Faleide and Professor Roy Helge Gabrielsen, I am grateful for your guidance, discussions, time and patience. Your help has been vital in the writing process and for the completion of this thesis. I would also like to thank Dr. Michel Herremans for preparing the acquired data for this study and for helping with problems and technical issues regarding the software.

TGS and Fugro are acknowledged for making seismic data available.

Thanks to my dear classmates at Geo for your support, discussions and motivation. I would especially like to thank everyone in the study hall (room 217). Finally, thanks to all my friends and family for your support and help while writing this thesis.

Abstract

The Bremstein Fault Complex is located on the Mid-Norwegian Continental Margin, where it functions as a boundary zone between the Halten Terrace and the Trøndelag Platform. There has been ongoing activity along the Bremstein Fault Complex since approximately the Middle Triassic, indicated by growth along individual faults. The fault complex was finalized by the downfaulting on the platform-terrace boundary, in the Late Cretaceous, resulting in individual terrace and platform structures.

The study focuses on the mechanisms responsible for the structural geometry of the Bremstein Fault Complex, with emphasis on the role of inherited Late Paleozoic structures and reactivated, as well as the extent and control of halokinesis and detachments. Detailed 2D seismic interpretation has been carried out, in order to constrain the timing of faulting and the subsequent structuring. The study area was divided into three segments, each segment represented by a key profile, illustrating the segments main structural style.

Four main tectonic events were recorded on the Bremstein Fault Complex: (1) the Permo-Triassic, (2) the Late Triassic-Early Jurassic, (3) the late-Middle Jurassic-Early Cretaceous and (3) the Late Cretaceous-Eocene. The events are evident in the seismic data in the form of structures related to growth faults. The tectonic movement, in the Permo-Triassic is most likely due to pre-existing zones of weakness, related to a Caledonian structural grain. Tectonic activity in the late-Middle Jurassic-Early Cretaceous has resulted in two distinct levels on the Bremstein Fault Complex, based on difference in fault populations and geometries. The evaporite layers functioned as a detachment, dividing the complex into pre-and post-evaporite structural settings.

Table of Contents

Chapter One: Introduction

Chapter One: Introduction

The structural framework of the mid-Norwegian continental margin, between 62° and 69°N, can be divided into platforms, terraces and basins. Cretaceous basins are located to the west, platforms and terraces to the east (Halten Terrace and Trøndelag Platform) and fault complexes in between (Bøen et al., 1984; Brekke, 2000; Faleide et al., 2008; Marsh et al., 2010). On the Norwegian continental margin a number of fault complexes exist, with old weakness zones inherited from the Caledonian Orogeny. Reactivation of these pre-existing basement structures is suggested to be the reason for the development and distribution of the complex structural elements.

The Jurassic to Early Cretaceous aged Bremstein Fault Complex located on the Halten Terrace and Trøndelag Platform boundary, approximately 150-250 km northwest of the Norwegian mainland, is the primary focus in this study (Figure 1-1). The interest in the Halten Terrace and its near surroundings has increased progressively since the acquisition of the first seismic data in 1969 and the distribution of the first exploration licenses in 1980 (Bukovics et al., 1984; Koch & Heum, 1995; Brekke, 2000). Petroleum exploration has thus provided invaluable geological knowledge, by way of both 2D and 3D seismic, as well as a large number of wells drilled.

The main objective is to analyze and interpret the structural setting for the Bremstein Fault Complex, to define the structural geometry and possibly determine the mechanisms responsible for the development. The mechanisms that will be analyzed in this study are: the effect and extent of halokinesis and detachments, and the possibility of inherited Late Paleozoic structures and reactivation. The presence of a Triassic detachment zone, is widely documented, in adjacent areas like the Åsgard area (Marsh et al., 2010), the Nordland Ridge/Revfallet Fault Complex (Pascoe et al., 1999; Dooley et al., 2003; Richardson et al., 2005), the southern Bremstein Fault Complex /Frøya High (Wilson et al., 2013; Bell et al., 2014) and in general discussions regarding Halten Terrace (Withjack et al., 1989; Withjack & Callaway, 2000; Withjack et al., 2002). Consequently, an evaporite-detachment is also expected in the Bremstein Fault Complex (Withjack et al., 1989; Withjack & Callaway, 2000).

Inherited Late Paleozoic structures have also been of interest for several years, and have been the topic of several publications (Bukovics et al., 1984; Doré et al., 1997; Osmundsen et al., 2002; Osmundsen & Ebbing, 2008; Breivik et al., 2011). However, due to lack of seismic data with sufficient resolution at depth, the claims of a structural grain controlling the structural settings of the Halten Terrace, has until present been speculative.

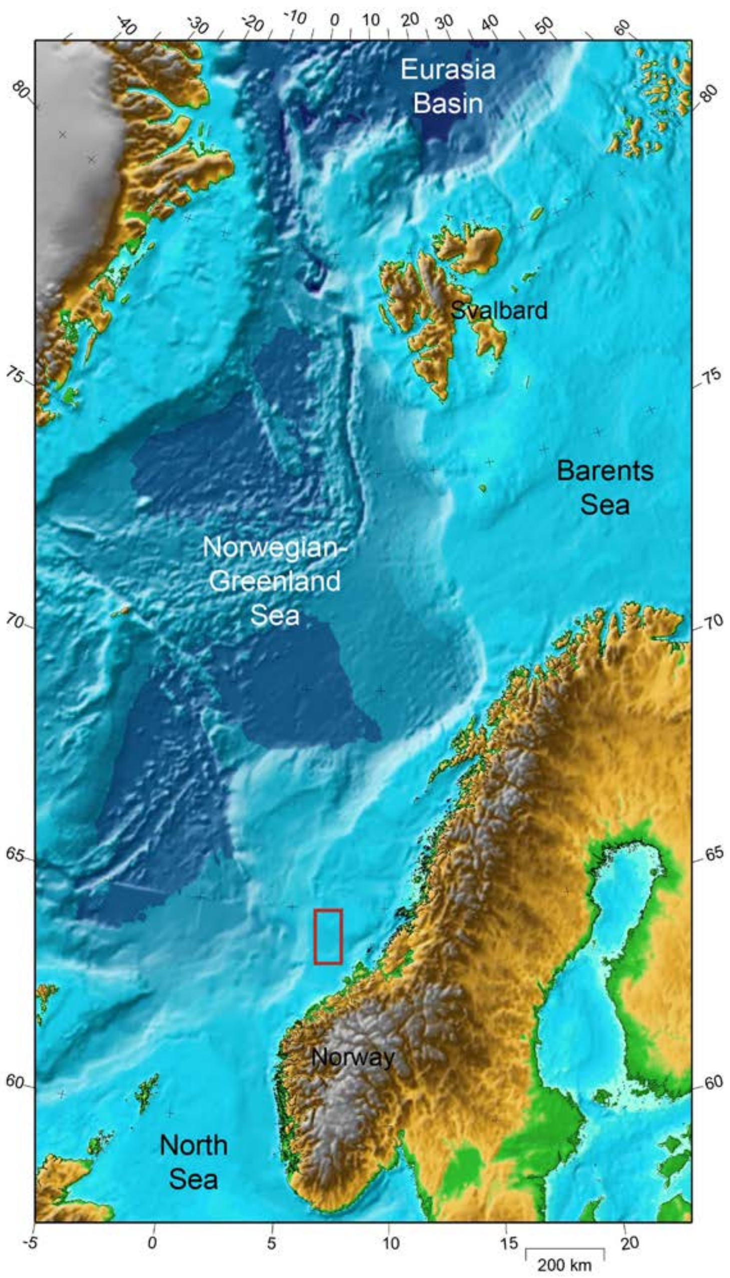


Figure 1-1 The Halten Terrace is found on the Mid-Norwegian Continental Margin, approximately 150-250 km northwest of the Norwegian city of Trondheim. The red box in the figure illustrates the study area. Modified after Faleide et al. (2008).

Chapter Two: Regional Framework

Chapter Two: Geological Framework

2.1 Regional geology

The Mid-Norwegian Continental Margin is one of three provinces located on the Norwegian continental shelf. It is a passive continental shelf stretching from the North Sea to the Barents Sea. The margin was formed by the opening of the NE Atlantic Ocean, following a number of well-documented rift episodes and phases of extensional tectonics, succeeding the compressional regime of the Caledonian orogeny (Bukovics et al., 1984; Price & Rattey, 1984; Blystad et al., 1995; Gabrielsen et al., 1999; Pascoe et al., 1999; Brekke, 2000; Skogseid et al., 2000; Færseth & Lien, 2002; Osmundsen et al., 2002; Marsh et al., 2010).

The Caledonian orogeny, formed by the collision of the Greenland-Laurentian Plate and the Fennoscandian-Russian Plate (Bukovics et al., 1984), came to an end in the late Siluran-Early Devonian. This resulted in orogenic collapse, back-sliding of the nappe pile, erosion of the uplifted mountain belt and deformation of the metamorphic basement (Bukovics et al., 1984; Doré et al., 1999). Several intramontane extensional basins were also formed at this time (Gabrielsen et al., 1984; Skogseid et al., 2000; Osmundsen et al., 2002). The deformational activity continued, leading to sinistral movement and regional crustal extension in the Middle Devonian-Early Carboniferous (Bukovics et al., 1984). The main phases of extension in the Late Paleozoic-Early Mesozoic, took place in mid-Carboniferous, Carboniferous-Permian, and Permian-Triassic time (Ziegler, 1988; Tsikalas et al., 2012)

In the Late Carboniferous-Late Permian the tectonic activity and crustal extension increased (Bukovics et al., 1984; Tsikalas et al., 2012). Fault activity in the Late Permian-Early Triassic, resulted in an extensive block-faulted terrain, visible beneath the Trøndelag Platform and Halten Terrace (Blystad et al., 1995)(Figure 2-1). A similar Paleozoic-Early Mesozoic structural grain has also been interpreted off NE Greenland (Doré et al., 1999; Skogseid et al., 2000). The specific timing and extent of this Permo-Triassic event is though uncertain and several extensional phases have been proposed i.e. Late Carboniferous-Early Permian, earliest Permian, Late Permian, Early Triassic and early to late Triassic (Bukovics et al., 1984; Brekke & Riis, 1987; Blystad et al., 1995; Pascoe et al., 1999; Corfield & Sharp, 2000; Skogseid et al., 2000; Richardson et al., 2005; Marsh et al., 2010). However, there is a consensus among authors, that the distributions of these earlier extensional structures controlled the geometry and location of Jurassic faults (Gabrielsen et al., 1999; Brekke, 2000; Bugge et al., 2002; Osmundsen et al., 2002), as well as the thickness of the post-rift Triassic deposits (Müller et al., 2005; Richardson et al., 2005; Marsh et al., 2010). Among the Triassic post-rift deposits are two evaporite layers (Blystad et al., 1995). These possessed the abilities to assert control over the Jurassic structural evolution, by fully or partially separating the deformation in the sub-evaporite strata from the overlying Jurassic successions (Elliott et al., 2012).

The most significant phase of rifting occurred between the Late Jurassic and Early Cretaceous (Richardson et al., 2005), following a period of minor tectonic activity in the Early to Middle Jurassic (Hollander, 1984; Swiecicki et al., 1998). An approximately E-W principal stress direction was regionally prevalent, indicated by the close-to-northerly trend of the Jurassic basins, e.g. the Halten Terrace (Doré et al., 1999)(Figure 2-1).

A shift in the extensional stress field vector from W-E to NW-SE in association with the northward propagation of the Central Atlantic spreading, is recorded in the Early Cretaceous (Doré et al., 1999). This change in direction might be a continuation of Devonian extensional shear zones and detachments (Bugge et al., 2002) and is evident by Cretaceous structures cutting the configuration of Paleozoic structures and basins (Osmundsen & Ebbing, 2008). Defining the timing of the late-Middle Jurassic to Cretaceous tectonic event is however under debate. Rifting in the late-Middle Jurassic to Late Jurassic and the earliest Cretaceous is evident (Blystad et al., 1995; Doré et al., 1999; Brekke, 2000; Faleide et al., 2008), but there is no consensus on how far into the Early Cretaceous the rifting preceded. Some authors attribute the Cretaceous structuring to rift activity, based on evidence of an Aptian-Albian rift event in the Vøring Basin, offshore UK (Doré et al., 1997; Doré et al., 1999), on East Greenland and in the SW Barents Sea (Tsikalas et al., 2012). However, Færseth and Lien (2002) have argued that the Cretaceous was a period of tectonic quiescence and that the structuring can be explained without invoking tectonic activity.

A new extensional tectonic event characterized by faulting, erosion and differential subsidence, followed in the mid-Cretaceous (Gabrielsen et al., 1984). In some areas the event only lasted to approximately Cenomanian times, while in other areas there are indications of continued activity throughout the Late Cretaceous (Doré et al., 1997). The mid-Cretaceous has also been proposed to be the initiation period for the major fault trends found on the Mid-Norwegian Continental Margin, i.e. N-S, NE-SW and ENE-WSW (Gabrielsen & Robinson, 1984). From the Late Cretaceous the rift activity increased and the evolution of the Norwegian-Greenland Sea area was dominated by regional crustal extension, focused on the future break-up axis (Bukovics et al., 1984).

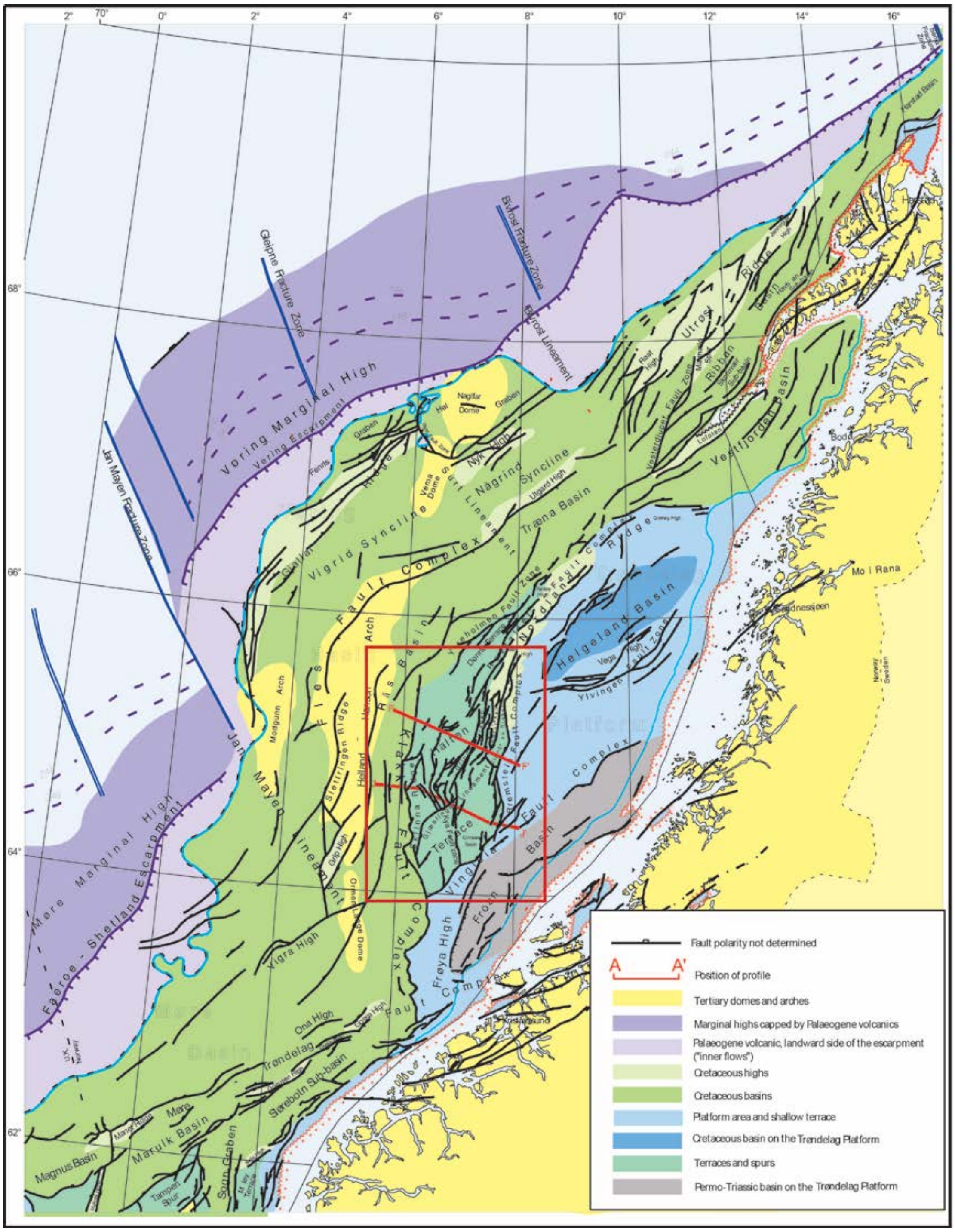


Figure 2-1 Main structural elements of the Mid-Norwegian Margin, including the Halten Terrace. Red transects indicate location of profiles F-F´ (Figure 2-2) and J-J´ (Figure 2-3). Modified after NPD (2014) and Blystad et al. (1995).

2.2 Structural elements

To be able to analyze and describe the tectonic setting and evolution of the Halten Terrace, the surrounding structures and architecture must be taken into consideration. Therefore the adjacent elements must be included in the geological framework. In the section below, a short description of the Halten Terrace, the Bremstein Fault Complex and a few of the adjacent structural elements have been provided.

2.2.1 Halten Terrace

The Halten Terrace (Figures 2-1) is a 10,400km^2 heavily block-faulted rhomboidal structure, roughly 80 km wide and 130 km long (Blystad et al., 1995). To the east and northeast the Bremstein Fault Complex separates the terrace from the Trøndelag Platform. In the southeast the Vingleia Fault Complex separates it from the Frøya High. The Klakk Fault Complex located west and northwest separates it from the Møre and Rås basins, whilst the northern part of the terrace is jointed to the shallower Dønna Terrace. Internally the Halten Terrace consists of the Sklinna Ridge, Grinda Graben (Figure 2-2), Kya Fault Zone (Figure 2-3) and Gimsan Basin (Figure 2-3), as well as a complex pattern of extensional faults with dominantly NE-SW and N-S orientation (Bukovics et al., 1984; Blystad et al., 1995).

The formation of the Halten Terrace started during the late-Middle Jurassic, when the Halten Terrace and the Trøndelag Platform was part of the same sedimentary basin. Fault activity prevailed into the Early Cretaceous along the terrace boundary, but by the mid-Cretaceous fault activity ceased (Bukovics et al., 1984). In the early-Late Cretaceous (Cenomanian/Turonian) the Halten Terrace was subjected to down-faulting. This resulted in the separation of the Halten Terrace from the Trøndelag Platform, and the formation of the Bremstein and Vingleia Fault Complexes. A Late Cretaceous rift event is also registered on the Halten Terrace, focused on the eastern boundary faults (Blystad et al., 1995).

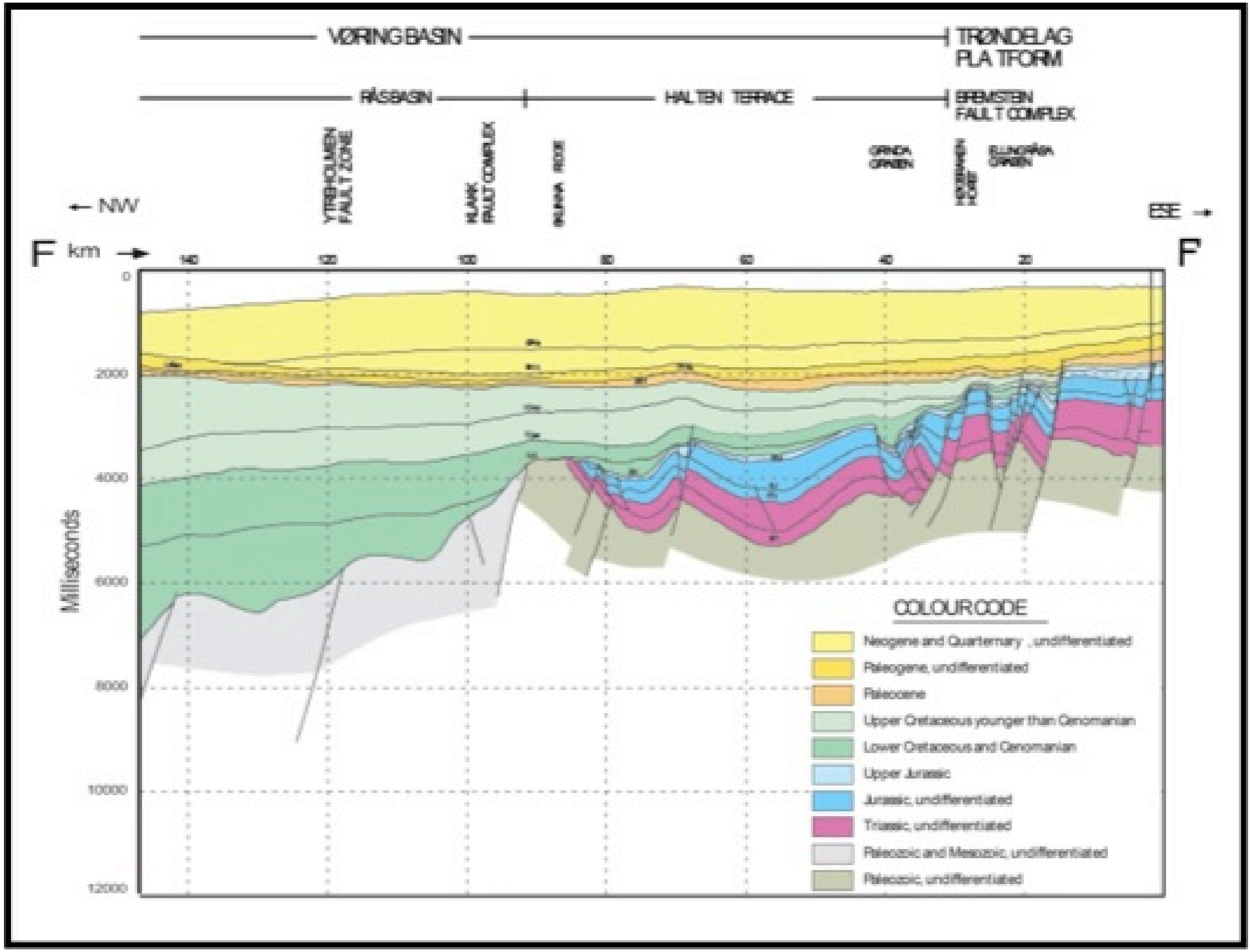


Figure 2-2 The composite profile of F-F´. The location of the profile is shown in Figure 2-1 and the lithology is given by the colored legend. Modified from Blystad et al. (1995).

2.2.2 Bremstein Fault Comple

The Bremstein Fault Complex (Figures 2-1, 2-2 & 2-3), formerly a part of the Kristiansund-Bodø Fault Complex (Gabrielsen & Robinson, 1984), is approximately 200 km long and 10 km across (Wilson et al., 2013). The structure terminates against the Rødøy High in the north, the Vingleia Fault Complex in the south and also functions as a boundary zone between the Halten Terrace and Trøndelag Platform (Blystad et al., 1995). The geometry of the Bremstein Fault Complex varies from north to south, with fault trends ranging from NNE, N and NNW. The northern part is dominated by a simple listric fault with associated salt-buffered faulting, while the southern segment is dominated by a ramp-flat-ramp geometry (Osmundsen et al., 2002; Osmundsen & Ebbing, 2008). There has been activity ongoing along the Bremstein Fault Complex since approximately the Middle Triassic, indicated by growth along individual faults. The major periods of movement coinciding with the regional rift phases i.e. the Late Triassic to Early Jurassic, the Late Jurassic and the Late Cretaceous (Blystad et al., 1995). The Early Cretaceous and the early-Late Cretaceous rift events controlled the final separation of the Halten Terrace and Trøndelag Platform (Brekke, 2000).

2.2.3 Trøndelag Platform

The Trøndelag Platform (Figures 2-1, 2-2 & 2-3) is situated to the east of the Halten Terrace and the Bremstein Fault Complex. It is one of the main structural elements on the Norwegian Continental Shelf and was introduced for the first time in the 1980´s (Hollander, 1982; Gabrielsen et al., 1984). It is a rhomboidal structure with several subsidiary elements i.e. the Nordland Ridge and Froan Basin. The main tectonic episode on the Trøndelag Platform took place between the Carboniferous and the Late Permian (Brekke, 2000). This is evident by an extensive block-faulted basement topography (Bukovics et al., 1984; Osmundsen et al., 2002) extending westwards, as the platform at this time formed part of a larger sedimentary basin (Gabrielsen et al., 1984). Tectonic activity is again evident in the middle to late Triassic times and the late-Middle Jurassic-Early Cretaceous. The platform was again effected by rifting and differential subsidence in the Late Cretaceous, evident by the separation of the Halten Terrace from the Trøndelag Platform (Bukovics et al., 1984; Brekke, 2000).

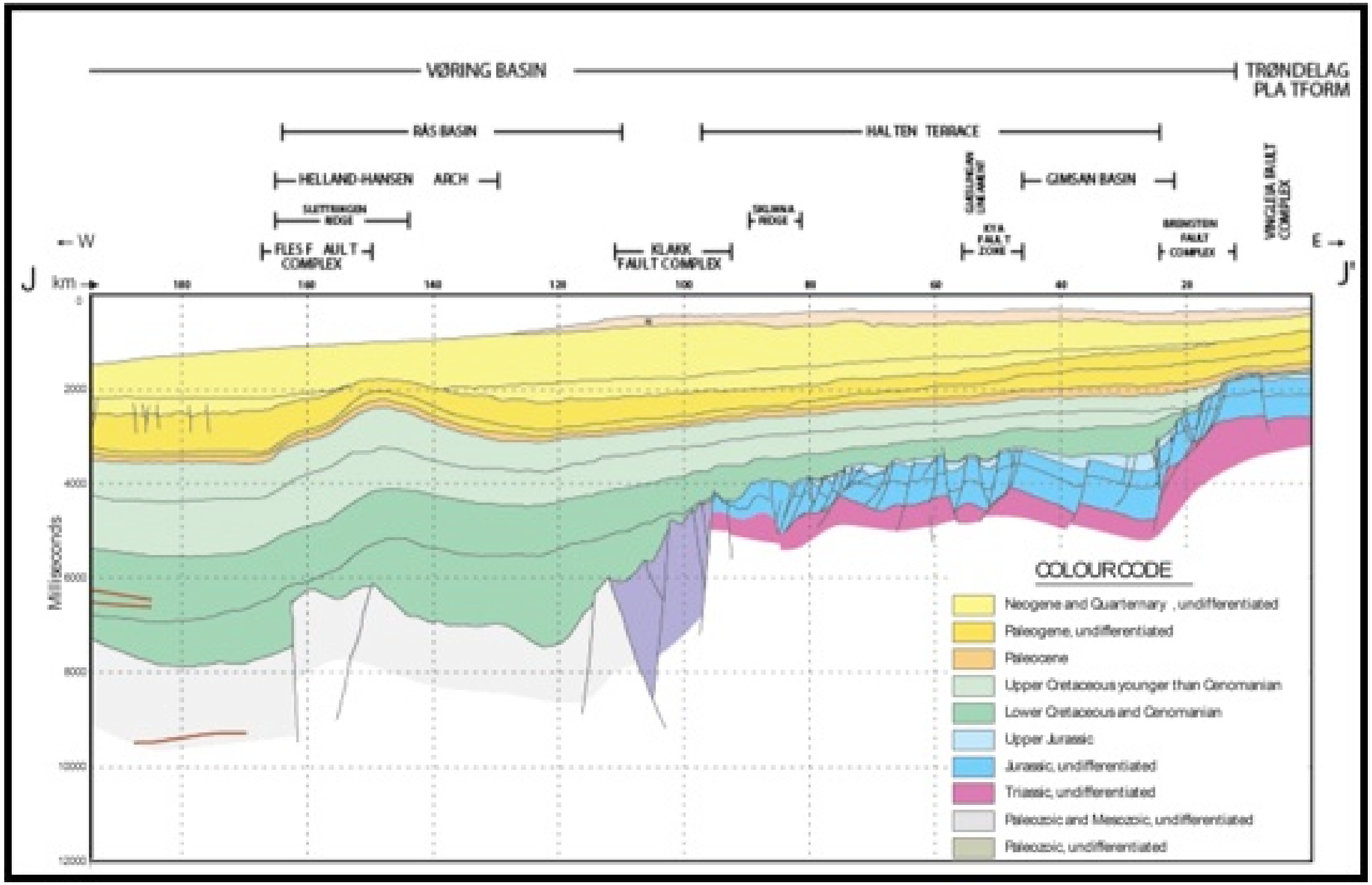


Figure 2-3 The composite profile of J-J. The location of the profile is shown in Figure 2-1 and the lithology is given by the colored legend. Modified from Blystad et al. (1995).

2.2.4 Nordland Ridge

The Nordland Ridge (Figure 2-1) is a sub-element of the Trøndelag Platform and is located to the north of the Halten Terrace and north to NE of the Bremstein Fault Complex. The structure has previously been regarded as the northern part of the Kristiansund-Bodø Fault Complex by Gabrielsen and Robinson (1984) and was first described by Rønnevik et al. (1975). Formation of the Nordland Ridge started around the Late Carboniferous-Early Permian time, with continued activity in the Triassic and Jurassic, culminating in the late-Middle Jurassic - Early Cretaceous with extensive erosion and uplift (Bøen et al., 1984; Blystad et al., 1995; Brekke, 2000).

2.2.5 Vingleia Fault Complex

The Vingleia Fault Complex (Figures 2-1 & 2-3) is a NE-SW trending element located to the south of the Halten Terrace, functioning as a boundary between the Halten Terrace, the Bremstein Fault Complex and the Trøndelag Platform/Frøya High. Faults of listric nature, originating in the Middle and Late Jurassic are identified as the main separation mechanism. However fault movement along the Vingleia Fault Complex has also been registered during the Triassic, Jurassic and Cretaceous, resulting in fault trends from N-S, NE-SW, ENE-WSW and WNW-ESE (Blystad et al., 1995).

2.2.6 Froan Basin

The Froan Basin (Figure 2-1) was first defined by Gabrielsen et al. (1984) in connection with studies of the Trøndelag Platform. The basin has also been called the Hitra Basin, in several publications (Bukovics et al., 1984; Bøen et al., 1984). The structure is located to the SE and south, of the Halten Terrace and Trøndelag Platform. It consists of Late Permian-Early Triassic strata deposited in half grabens of alternating polarity along strike. The age of the Froan Basin is most likely Permo-Triasssic, whilst the block-faulted floor is defined as late-Early Permian. Minor reactivation in the Jurassic is evident by faulting. Uplift and erosion affected the Frøya High and the southwestern part of the Froan basin during the Late Jurassic (Blystad et al., 1995).

2.2.7 Sklinna Ridge

The Sklinna Ridge (Figures 2-1, 2-2 & 2-3) previously part of the Nidaros Arch (Bukovics et al., 1984), was early on descried as an uplifted flank along the Halten Terrace (Heum et al., 1986). It is the westernmost margin of the Halten Terrace, bounded by the Klakk Fault Complex. The formation of the Sklinna Ridge coincides with the formation of the Halten Terrace. The structure was formed as a flank uplift along the Klakk Fault Complex, during the Middle to Late Jurassic and possibly the Early Cretaceous (Aptian/Albian) (Blystad et al., 1995). Due to the presence of Triassic evaporites on the Halten Terrace and little or none evaporites elsewhere, Heum et al. (1986) proposed that structures located around the Halten Terrace functioned as barrier-structures during the Cretaceous. The Sklinna Ridge might have been a part of this barrier, separating the Halten Terrace from normal marine conditions.

2.3 Stratigraphy

The stratigraphic framework for the mid-Norwegian Continental Margin and the Halten Terrace is summarized in Figure 2-4, and outlined by Dalland et al. (1988) and Müller et al. (2005).

In the Late Permian, the mid-Norwegian margin was subjected to a regional transgressive event (Swiecicki et al., 1998), following a period of crustal extension in the Late Carboniferous to Middle Permian (Bugge et al., 2002; Müller et al., 2005). This resulted in a marine depositional environment, with deposition of Permian carbonates and clastics (Heum et al., 1986). Uplift, syn-sedimentary faulting and erosion followed in the Lower Triassic, with extensive sea-level fluctuations and an arid to semi-arid paleoclimate (Müller et al., 2005). The mid-Norway area was at this time located towards the center of the Pangean supercontinent, at around 25° north of the equator (Swiecicki et al., 1998). Towards the late-Early Triassic there was a switch in the depositional environment. The sedimentary units from this time indicate a marginal marine setting, reflecting a reduction in subsidence and tectonic activity. This indicates that towards the Middle Triassic there was a transition from a late syn-rift to an early post-rift setting (Müller et al., 2005).

By the Middle Triassic, marginal marine to continental-fluvial settings transpired. This might be the result of a decrease in accommodation, relative to the rate of sedimentary input (Müller et al., 2005). By the early-Late Triassic a new depositional environment arose, reflecting a shift in paleogeography and paleoclimate (semi-arid to arid). On a global scale, the Middle/Late Triassic boundary marks the dispersal of Pangea and the initiation of continental drifting. The period was therefore tectonically active, with regional uplift and large fluctuations in sea-level (Hollander, 1984; Müller et al., 2005). Two evaporite units of marine origin, with interbedded halite and mudstone were deposited at this time, in the Anisian – Ladinian (Heum et al., 1986; Swiecicki et al., 1998).

In the latest Triassic to Early Jurassic a continental environment emerged, with shallow lacustrine basins and alluvial floodplain deposits. The paleoclimate also changed from semi-arid to more humid (Müller et al., 2005). The change in paleoclimate was related to the northwards drift of the continental plate (Swiecicki et al., 1998). Evidence of the climate change can be seen in the sedimentary deposits; change from reddish-brown to more greenish-gray floodplain sediments, the occurrence of paralic coal-bearing sediments (Åre formation) and the disappearance of evaporite deposits (Swiecicki et al., 1998; Müller et al., 2005).

In the Early Jurassic to Early Cretaceous a fluvial-deltaic and increasingly open marine environment dominated (Corfield & Sharp, 2000), with deposition of the Båt, Fangst and Viking Groups, above Triassic sedimentary units. The Late Jurassic Båt Group is not overly represented in the study area, especially along ridges (Sklinna and Nordland Ridge) and uplifted footwalls (Bremstein Fault Complex). This is due to erosion of the Base Cretaceous Unconformity (Wilson et al., 2013), induced by the Kimmerian tectonic phase, eustatic sea-level drop and the temporal restriction of marine sedimentation (Hollander, 1984). In areas that evaded erosion, complete stratigraphic units of the Not, Garn, Melke and Spekk Formations can be seen. These were most likely deposited as syn-tectonic units, in a paralic-to-shallow-marine sand- (Garn and Ile Formations) and mud-rich (Not and Ror Formations) setting (Elliott et al., 2012; Bell et al., 2014). In the late-Middle Jurassic the mid-Norwegian Shelf was drowned, resulting in the deposition of shale and clay stones (Melke and Spekk Formations) in a fully marine, sediment-starved basin (Swiecicki et al., 1998; Richardson et al., 2005; Marsh et al., 2010; Elliott et al., 2012)

Above the Base Cretaceous Unconformity, Cretaceous shallow to deep marine sedimentary units of the Cromer Knoll and Shetland Groups were deposited (Dalland et al., 1988).

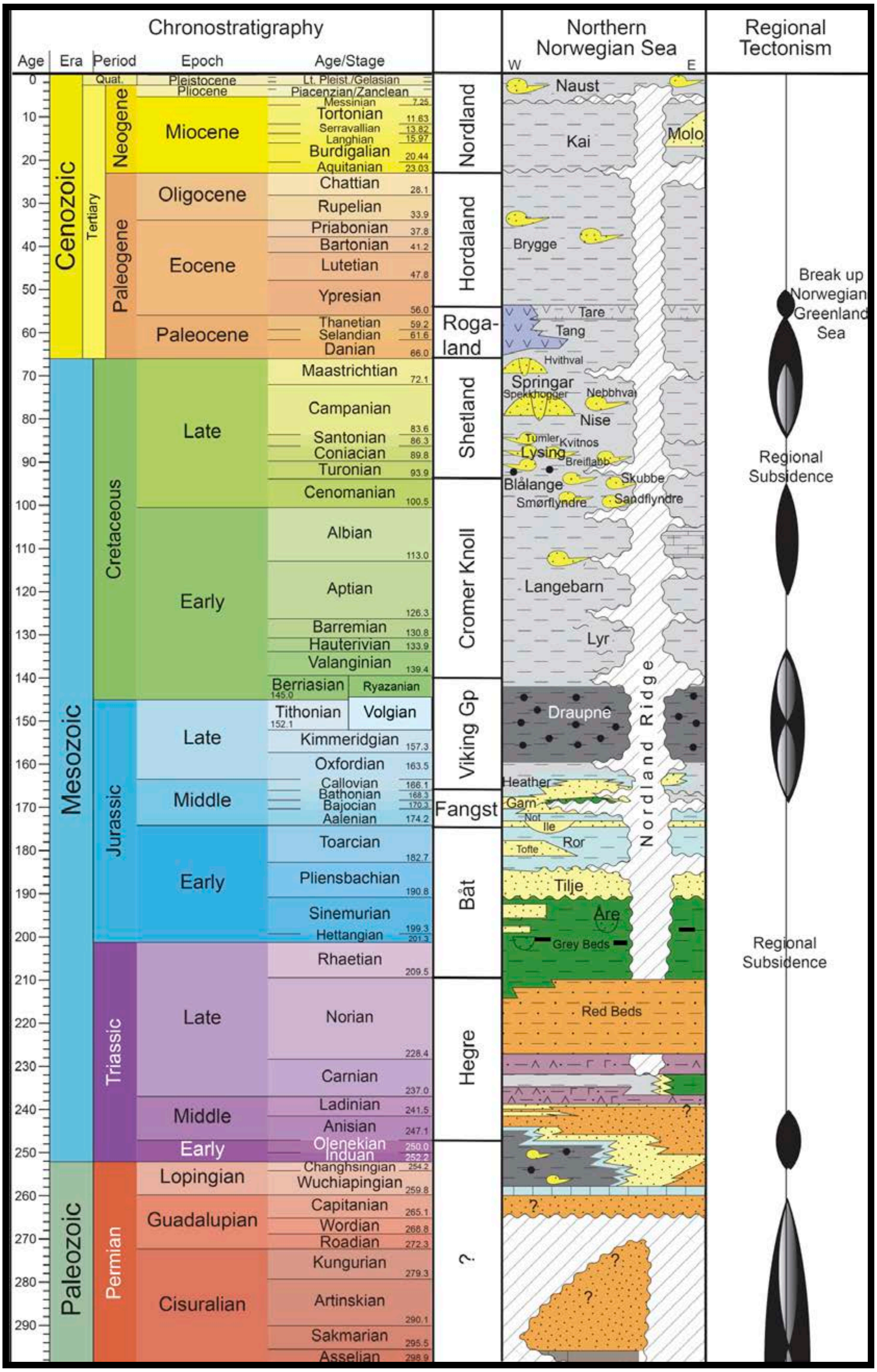


Figure 2-4 A schematic diagram of the chronostratigraphy and Permian and Mesozoic lithostratigraphy found on the Norwegian Continental Margin, with the main tectonic events illustrated. Modified after Gradstein et al. (2010) and Tsikalas et al. (2012).

Chapter Three: Seismic Interpretation and Results

Chapter Three: Seismic Interpretation

Several sets of regional and local 2D seismic lines were analyzed in the present study, of which a few have been selected for detailed interpretation (Figure 3-1). To enhance the usefulness of the structural analysis, the relationship between the regional rift episodes and phases of tectonic activity in the study area was particularly emphasized. Defining the complex geometry of the Bremstein Fault Complex, and to possibly determine the mechanisms responsible for its development was also focused upon. Some of the topics, which are analyzed and discussed, are the possibility of inherited Late Paleozoic structures controlling the structural setting, and also the effect and extent of salt tectonics.

The seismic analysis was focused upon the northern part of the Halten Terrace (Chapter 3.4). Particularly one diagonal corridor comprising of several lines oriented NW-SE was studied in detail. This will provide a particularly good representation of the N-S oriented Bremstein Fault Complex, which defines the transition between the Halten Terrace and the Trøndelag Platform (Blystad et al., 1995; Osmundsen & Ebbing, 2008). The study also includes a wider and more general geological analysis. This analysis places the Bremstein Fault Complex into a more regional perspective.

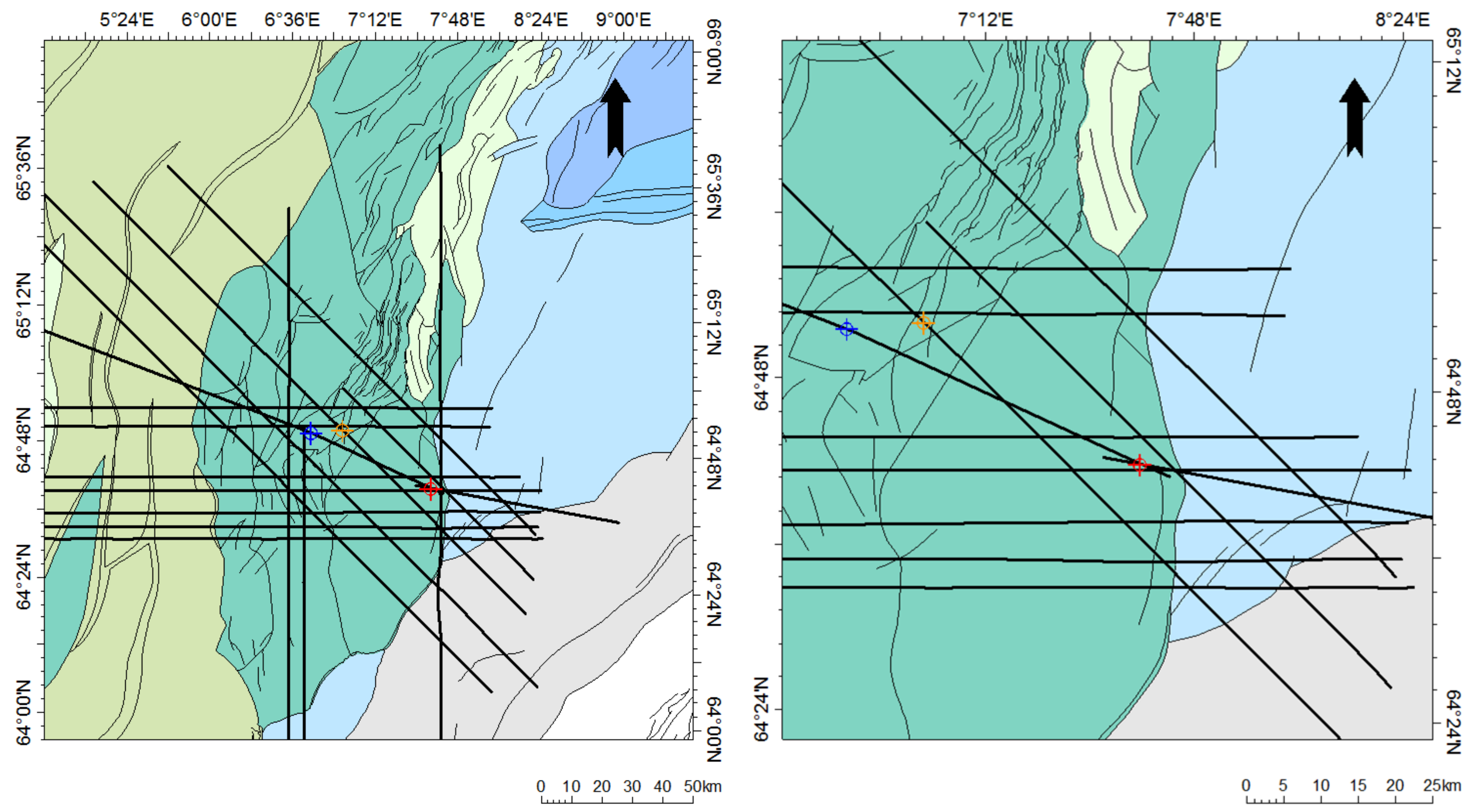


Figure 3-1 Map illustrating the seismic 2D lines and the wells used in the study. Left: The 16 seismic lines covering the Halten Terrace. Right: The 11 key profiles covering the Bremstein Fault Complex, illustrated with profile names i.e. I-XI.

3.1 Data

3.3.1 Seismic Data

One seismic survey, consisting of E-W, NW-SE and N-S-oriented 2D seismic lines, was used to form a spaced regional grid covering the Halten Terrace. The E-W oriented profiles provide the best coverage and orientation perpendicular to some of the structural trends on the Halten Terrace, like the Bremstein Fault Complex. These profiles where therefore used for the Bremstein Fault Complex study. The NW-SE (and one NNW-SSE) oriented profiles are sub-parallel to the diagonal section of the study area. Consequently the NW-SE oriented profiles have the best coverage of the Halten Terrace, making these profiles optimal for the general analysis. The regional N-S oriented profiles will not be presented here; they were however used to correlate the seismic interpretation of the E-W and the NW-SE oriented lines. After screening, a total of 16 2D seismic lines (Figure 3-1, Left) were chosen for the study. All of the chosen seismic lines record to 10 s TWT with good to excellent resolution, showing structural elements down to 8-9 s TWT. The vertical and lateral continuity is relatively good, with structural and stratigraphic visibility down to about 5,5 - 6 s TWT. There is good to excellent imaging of the fault planes at depth, particularly for large-magnitude, moderate- to low-angle normal faults.

To distinguish the profiles that transect important features, the profiles have been labeled I – XI (Figure 3-1, Right). In the Bremstein Fault Complex study, the Complex was divided into three segments, each segment representing a clear change in structural style along strike. Several seismic lines cross the same segment; a key profile has therefore been selected for each segment. This key profile was used to describe the whole segment and will represent the segments main structural style. Profile I (oriented E –W) represents Segment 1, profile V (oriented E – W) represents Segment 2 and profile XI (oriented NW-SE) represents Segment 3. Key Profile VIII (oriented NNW-SSE) and key profile IX (oriented NW-SE), as well as two close-ups, were chosen for the general geological analysis.

The available seismic data sets were not depth-converted. This means that the seismic lines are presented with the vertical axis in two-way travel time (TWT).

3.1.2 Well Data

The Mid-Norwegian Continental Shelf has been regarded a prolific hydrocarbon province (Rønnevik, 2000) with consistent exploration activity (NPD & OED, 2014; OED, 2014), since the spudding of well 7120/12-1 in 1980 (Jacobsen & van Veen, 1984). In this study three exploration wells have been integrated with the seismic data, to obtain the stratigraphic age of the seismic reflections and to control the seismic interpretations (Table 3-1). Two wells were tied to profile VIII (wells 6406/3-2 & 6407/6-3, Figure 3-2) and one to profile IX (well 6407/1-3, Figure 3-3). All the wells applied in the study are shallow wells, so that the deepest level penetrated is the Jurassic (the top Åre Formation, Table 3-2 & Figure 3-4). Information about the strata located below the top Åre Formation (Chapter 2.3, Figure 3-2) is scarce. However, a few publications have described the Late Permian to Triassic lithostratigraphy, based on information gathered from wells 6507/12-2, 6507/6-1, 6610/7-2 and 6510/2-1 (Jacobsen & van Veen, 1984; Heum et al., 1986; Pascoe et al., 1999; Müller et al., 2005; Richardson et al., 2005). The lithostratigraphy recorded by these wells includes two evaporite intervals (Chapter 2.3) from the Middle to Upper Triassic.

The well data, (Tables 3-1 and 3-2) were downloaded from the Norwegian Petroleum Directorate, FactPage.

Table 3-1 Well data regarding the wells used for the well-to-seismic correlation. The location of wells 6406/3-2 & 6407/6-3 can be seen in Figure 3-2 and well 6407/1-3 in Figure 3-3.

Wells	*6406/3-2*	*6407/1-3*	*6407/6-3*
NS UTM (m)	7195126,91	7195989,53	7176849,07
EW UTM (m)	397207,63	407531,49	436571,55
UTM zone	32	32	32
Drilled in license	91	73	92
Drilling operator	Den Norske Stats Oljeselskap	Den Norske Stats Oljeselskap	Den Norske Stats Oljeselskap
Drilling days	148	122	66
Entry date	28.06.86	17.09.83	13.12.86
Completion date	22.11.86	16.01.84	16.02.87
Type	Exploration	Exploration	Exploration
Status	P&A	P&A	P&A
Discovery	Oil	Oil/Gas	Gas/Condensate
KB (m)	22	29	29
Water depth (m)	300	286	222
TD (MD) [m RBK]	4523	4469	3220
Oldest penetrated level	Early Jurassic	Late Triassic	Late Triassic
Oldest formation	Åre Fm.	Grey Beds	Åre Fm.

Table 3-2 Formation tops of the wells used in this study. Wells 6406/3-2 and 6407/6-3 are illustrated in Figure 3-2 and well 6407/1-1 is illustrated in Figure 3-3.

Age	Group/Formation	6406/3-2	6407/1-3	6407/6-3
		Top MD (m)	Top MD (m)	Top MD (m)
Cenozoic	*Nordland Gp.*	322	315	251
	Naust Fm.		315	251
	Kai Fm.	1493	1449	1227
	Hordaland Gp.	1970	1763	1463
	Brygge Fm.	1970	1763	1463
	Rogaland Gp	2309	2213	1915
	Tare Fm.	2309	2213	1915
	Tang Fm.	2380	2300	1978
Cretaceous	*Shetland Gp.*	2437	2346	2069
	Springar Fm.		2346	
	Nise Fm.		2448	
	Cromer Knoll Gp.	3119	2601	2414
	Lange Fm.		2601	
	Lyr Fm.		3500	
Jurassic	*Viking Gp.*	3841	3521	2445
	Spekk Fm.	3841	3521	2445
	Melke Fm.	3867	3545	2451
	Fangst Gp.	3930	3600	2461
	Garn Fm.	3930	3600	2461
	Not Fm.	4017	3704	2492
	Ile Fm.	4069	3741	2548
	Båt Gp.	4128	3813	2639
	Ror Fm.	4128	3813	2639
	Tofte Fm.	4178		2691
	Ror Fm.	4203		2698
	Tilje Fm.	4285	3950	2727
	Åre Fm.	4496	4150	2902
Triassic	*Grey Beds*	Not penetrated	4455	Not penetrated
	Red Beds		Not penetrated	
	Upper Evaporite Layer			
	Lower Evaporite Layer			
	Red Beds			
	Basement			

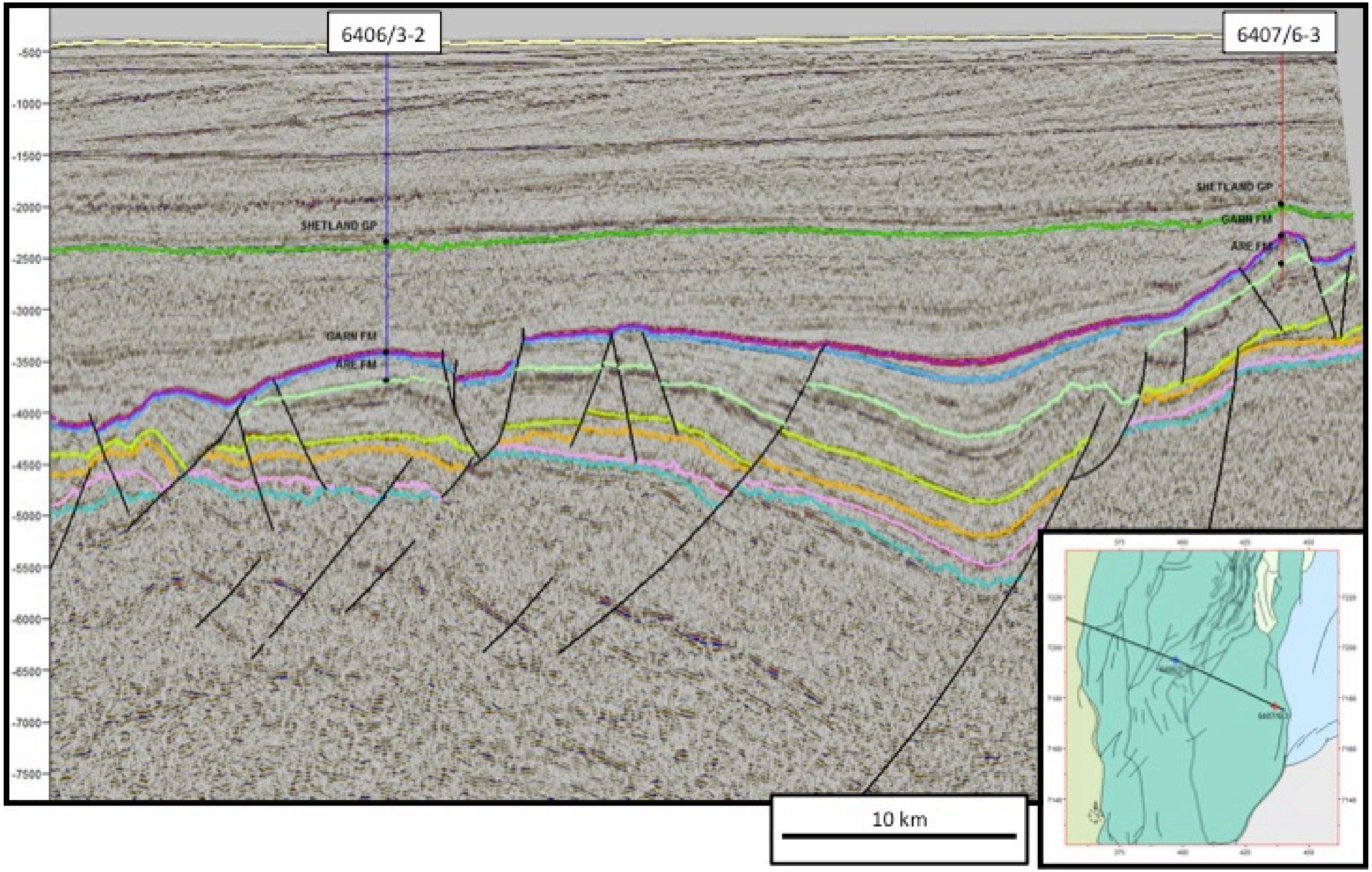


Figure 3-2 Seismic profile VIII, illustrated with wells 6406/3-2 and 6407/6-3. The color-coding of the interpreted seismic reflectors is explained in Figure 3-5. A close-up of the wells can be seen in Figure 3-4.

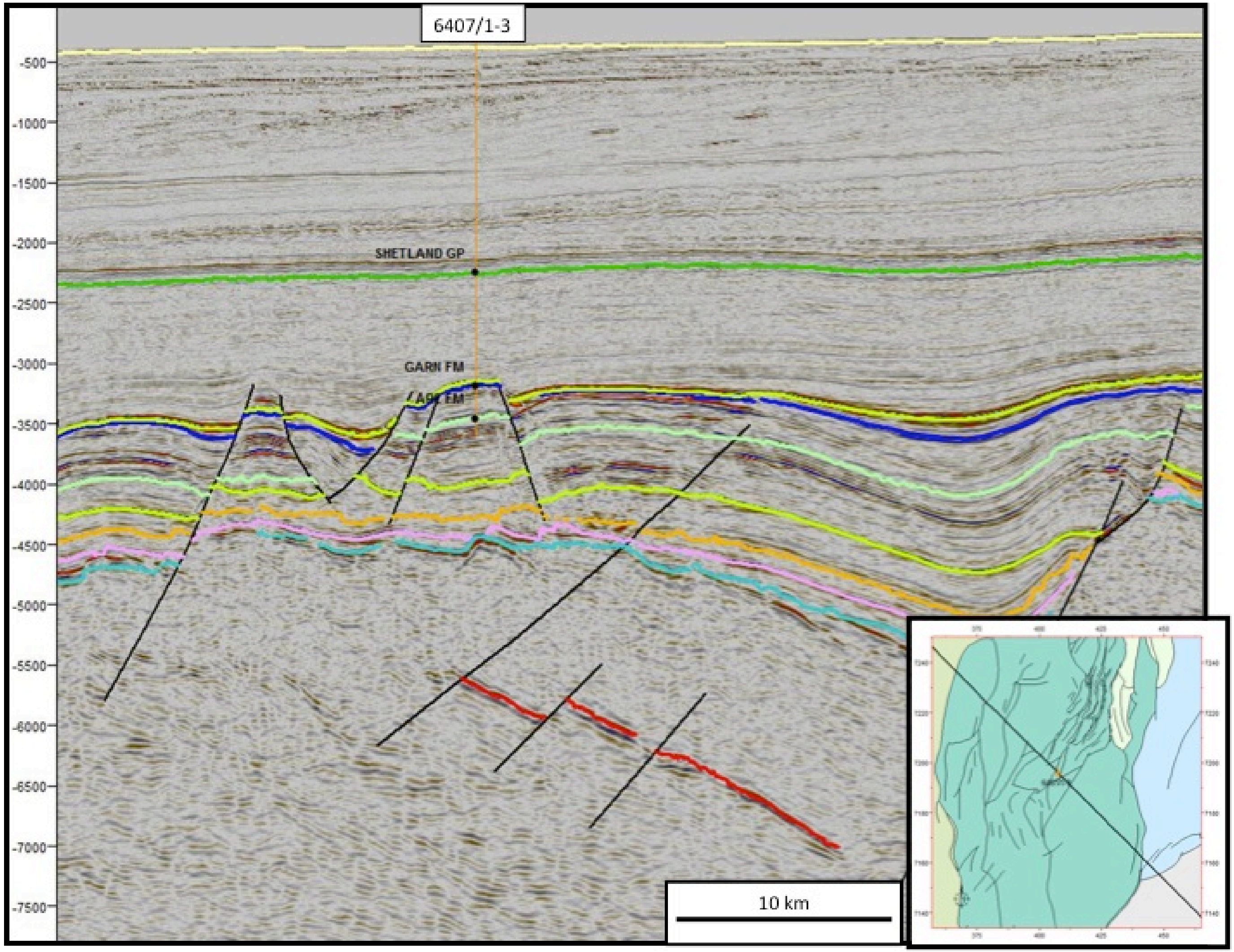


Figure 3-3 Seismic profile IX, illustrated with well 6407/1-3. The color-coding of the interpreted seismic reflectors is explained in Figure 3-5. A close-up of the wells can be seen in Figure 3-4.

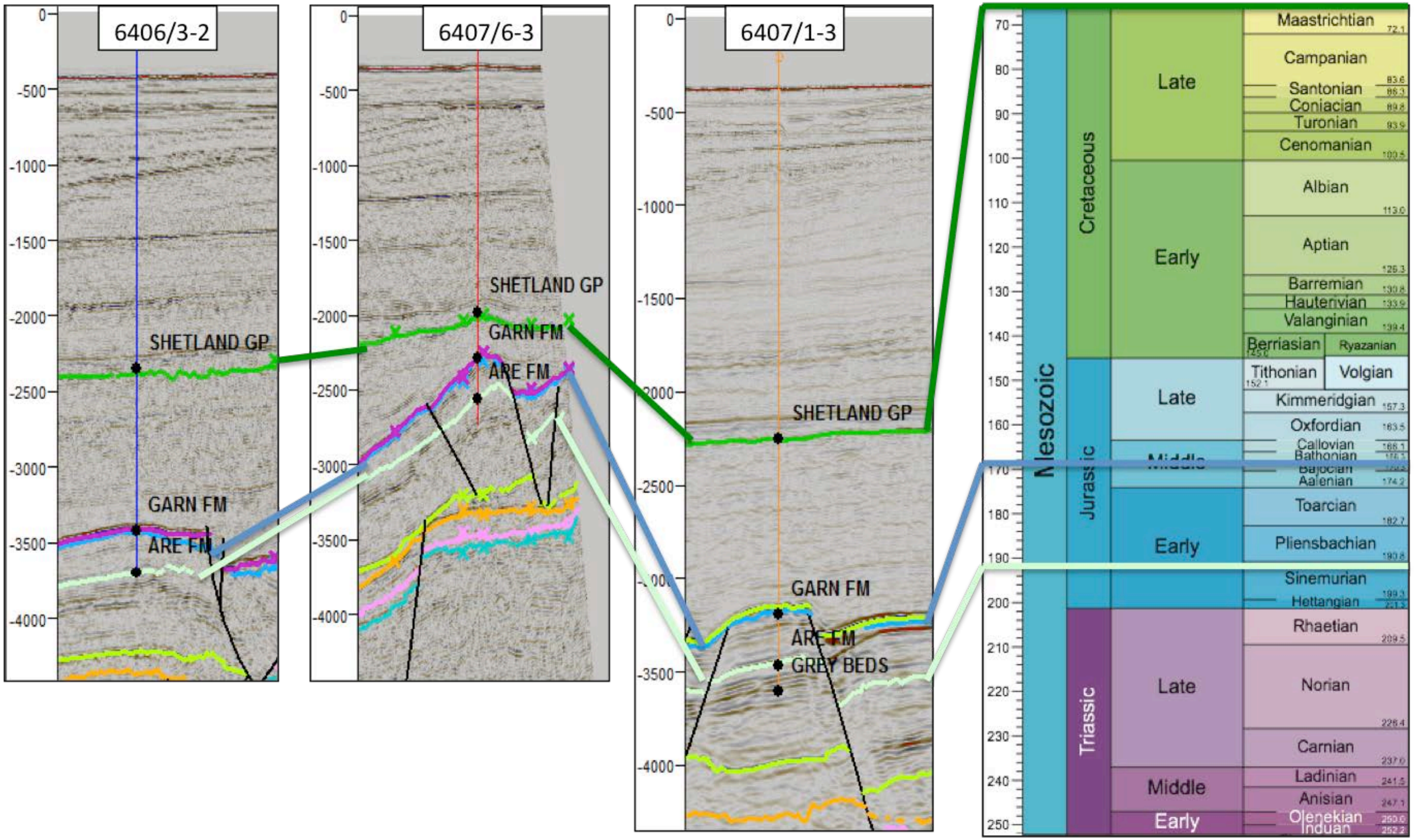


Figure 3-4 Well-to-seismic ties for wells 6406/3-2, 6407/1-3 and 6407/6-3, and their respective ages. The location of the wells can be seen in Figures 3-2 & 3-3.

3.2 Mapped lithostratigraphic units and Well ties

The 10 key reflection surfaces (Figure 3-5) that were chosen for the study of the Halten Terrace are described in this section. The description outlines their attributes, how they were selected, well correlation and how they perform in the study area.

The Base Cenozoic is represented by an intermediate to strong positive reflection. The reflection is relatively continuous with only a few reflection discontinuities due to faults, primarily affiliated with the Bremstein Fault Complex. The reflection was traced throughout the study area and was found at ± 2 s TWT on the Trøndelag Platform, between 2-2,5 s TWT in the Halten Terrace area and below 3 s TWT in the basin areas. The base of the Cenozoic is penetrated by all three wells and corresponds to the top of the Shetland Group (Figures 3-2 & 3-3).

The Base Cretaceous Unconformity (BCU) reflection was not correlated with any formation top in the well correlation analysis, but can be identified right above the top of the Garn Formation (Figures 3-2 & 3-3). The BCU is represented by a continuous reflection with strong negative amplitude. The only place where the BCU cannot be identified and mapped as a continuous reflection, is where the BCU is eroded down to pre-Cretaceous formations and in places where the reflection is faulted. The BCU is mapped at about 2 s TWT on the Trøndelag Platform and between 3-4 s TWT in the Halten Terrace area.

The top of the Garn Formation is characterized by a continuous, high amplitude positive reflection, which can be mapped throughout the study area. The reflection was mapped at about 2 s TWT on the Trøndelag Platform and between 3-4 s TWT in the Halten Terrace area, right below the base Cretaceous reflection. The top of the Garn Formation is penetrated by all three wells (Figures 3-2 & 3-3).

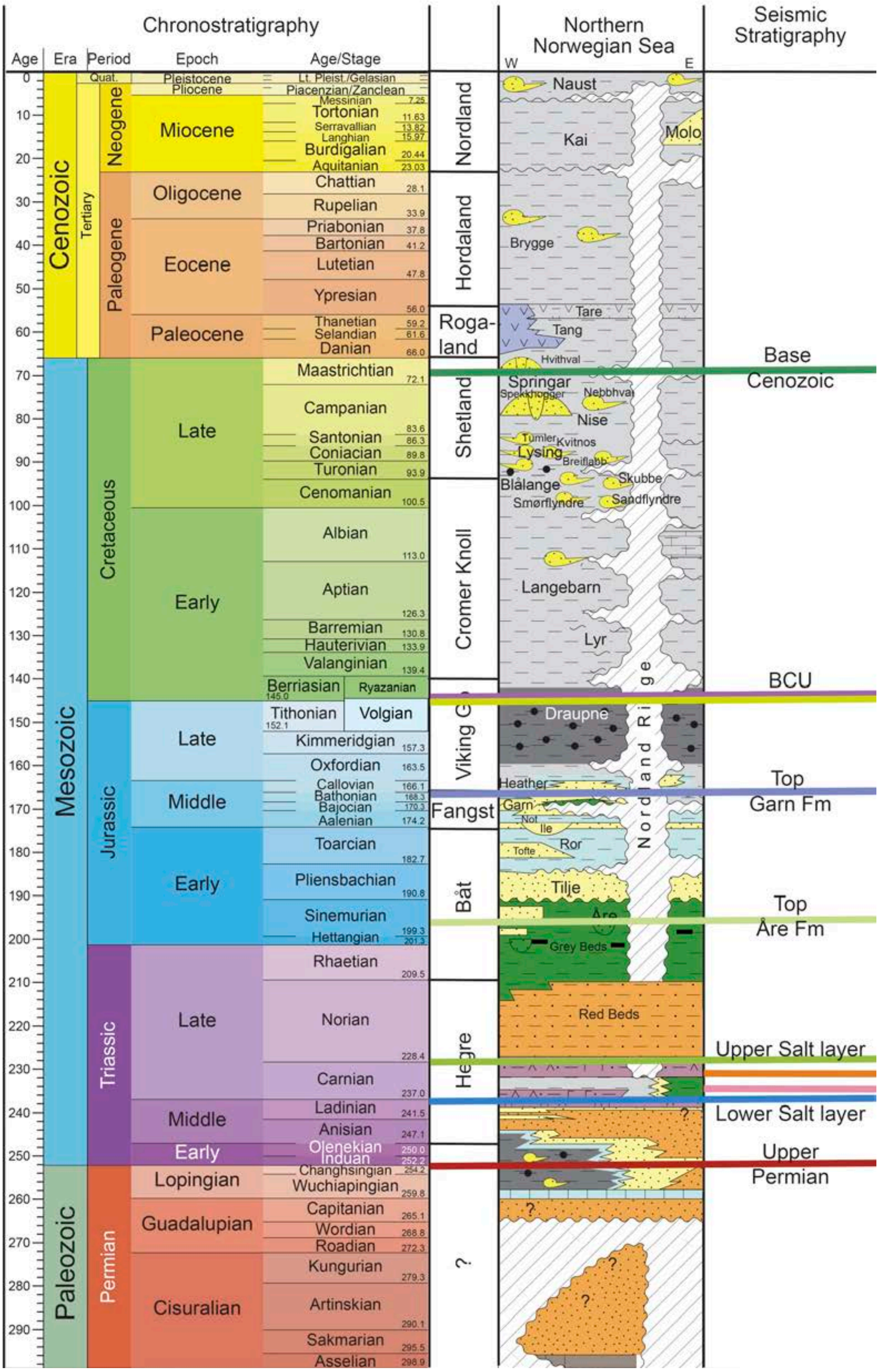


Figure 3-5 A schematic diagram of the chronostratigraphy, Permian and Mesozoic lithostratigraphy and the seismic stratigraphy found on the Halten Terrace. The seismic reflector color-coding will be used in all subsequent figures. Modified after Gradstein et al. (2010).

An intra-Jurassic reflection was mapped and found to correlate with the top of the Åre Formation (Figures 3-2 & 3-3). The reflection has a medium to high positive amplitude and is located around ± 4 s TWT in the Halten Terrace area, between 2-3 s TWT in the Bremstein Fault Complex and about 2,3 s TWT on the Trøndelag Platform. The reflection is hard to map throughout the study area, because of amplitude variations and reflection discontinuities.

Two semi-horizontal evaporite layers (Chapters 2.3 & 3.1.2) with an intra-evaporite sedimentary unit, were mapped between 3–3,5 s TWT on the Trøndelag Platform and between 4-5 s TWT on the Halten Terrace. The resolution quality for both units is generally good to excellent. The top and bottom reflections are characterized by continuous, moderate to high negative amplitude and occasionally a positive reflection with strong to moderate amplitude accompanies the base salt reflection (Figures 3-2 & 3-3). The intra-evaporite layers are characterized with internal reflections and transparency to varying degree, while the intra-evaporite sedimentary layer is typically characterized by discontinuous, low-amplitude reflections. Lateral thickness variations occur for both evaporite layers and in some areas structures like swells, pillows and walls can be seen.

The top Permian reflection (Figure 3-3) was mapped at around 4.5-5,5 s TWT below the Trøndelag Platform and between 5,5 – 6,5 s TWT below the Halten Terrace. The reflection is characterized by discontinuous, low to medium amplitude and was only interpreted on a few of the seismic lines due to the resolution constraint. A noteworthy point is the uncertainty associated with the top Permian reflection. Since none of the wells penetrate this level, the interpreted Top Permian is not well constrained. This means that the reflection might not be the correct top Permian reflection, but may still be a reflection of Permian age.

A reflection that might represent the basement was traced in a few of the seismic profiles (profiles I, II, IX and X). The reflection is located at about 7-8 s TWT below the Trøndelag Platform, on the eastern side of the Bremstein Fault Complex. The reflection is discontinuous, with low positive amplitude.

3.3 The Seismic Interpretation procedure

The technique used for seismic interpretation follows the general procedure of 2D seismic analysis (Herron, 2011). It starts with a general structural and stratigraphic interpretation, resulting in the investigation of specific structural geometries and their evolution. The initial structural and stratigraphic interpretations of selected key profiles were performed on hard-copy (paper) and Petrel, the seismic interpretation software manufactured by Schlumberger (Schlumberger, 2014). The interpretation in Petrel was performed with the use of seismic data, well data and well-ties. The information obtained, was then used to pick key horizons, selected key profiles, produce fault polygons/fault maps and a time-structure map.

All the available seismic surveys covering Halten Terrace were screened in Petrel. The surveys of highest quality, best coverage and clearest resolution were selected and interpreted. After the first screening of the seismic data, some of the lines were printed and examined on hard-copy. This was to ensure correct reflection picks, fault interpretations and interpretation of structural features. The hard-copy examination was especially important for the illustration and understanding of the salt coverage on the Halten Terrace and the structural variation of the Bremstein Fault Complex.

Following the hard-copy examination some corrections were made to the Petrel interpretation. Reflections were interpreted to best illustrate the structural features and sedimentary packages. Faults were interpreted to illustrate the range of structural styles and relationships occurring with both basement and the evaporite units, giving the opportunity to differentiate between thick-skinned faults (Chapter 3.4) and thin-skinned faults (Chapter 3.4) e.g. sub-evaporite restricted faults and supra-evaporite restricted faults. The interpretations were then correlated with wells, resulting in the ability to connect the sedimentary packages and faults to correct stratigraphic age and tectonic period (Chapter 3.2, Figures 3-2, 3-3 & 3-4).

With the information obtained from the reflection interpretation, maps were produced e.g. time-structure- and fault-map. The time-structure map illustrates the whole study area, from the Halten Terrace to the Trøndelag Platform, at the base of the Cretaceous. The fault maps or fault polygons (Figures 3-6 & 3-7) visualize the strike, dip and displacement variations of the faults present in the Bremstein Fault Complex and adjacent areas. However, the accuracy of maps generated from 2D seismic data can be questioned. The wide spatial gridding of the 2D lines will give rise to some inaccurate extrapolations and a "smoothing" effect on the surface structures, by the interpretation software.

3.4. Nomenclature

The following nomenclature was used in the description of structural trends and geometries, in the present study. The terms to be described are presented in italic and defined according to Twiss and Moores (1992) and Allaby (2008).

A ***terrace*** (e.g. the Halten Terrace) refers to a nearly flat portion of a landscape, terminated by a steep edge (Allaby, 2008). A ***master fault*** refers to a fault that has major displacement and accounts for most of the deformation (Twiss & Moores, 1992, p. 95). When the term ***listric fault*** is described without any further explanation, it refers to a concave upwards fault or a fault that characteristically decrease in dip with increasing depth (Twiss & Moores, 1992, p. 92; Allaby, 2008, p 338). A ***detachment fault*** is a low-angle fault that marks a major boundary between faulted and non-faulted rocks (Twiss & Moores, 1992, p. 93). A detachment may also refer to a zone (a weak layer in the stratigraphy, e.g. evaporites) where low–angle listric faults with the same general orientation joins a major low-angle fault at depth (Twiss & Moores, 1992, p. 123). A ***thick-skinned fault*** refers to a continuous fault that penetrates a whole sedimentary sequence including a ductile layer, which is displaced across the fault. A ***thin-skinned fault*** refers to a supra-evaporite restricted fault, with downwards termination in the evaporite layer (Wilson et al., 2013). ***Drag fault/-fold*** is the flexuring of bedding and cleavage traces along the margins of a fault plane, produced by displacement (Allaby, 2008). A ***ramp-flat-ramp*** structure is a flat area connected to two more steeply dipping fault segments (Twiss & Moores, 1992, p. 85). A ***rollover anticline*** is the downwarping of a hanging-wall block bounding a listric fault (Allaby, 2008). A ***graben*** is a down-dropped block bounded on both sides by conjugate normal faults that dip towards the down-dropped block (Twiss & Moores, 1992, p. 95). The structure is often associated with horst and relay-ramp structures. A ***relay-ramp*** is an extensional or contractional horizontal structure consisting of a zone where the fault segments overlap (Twiss & Moores, 1992, p. 84-85). A ***breached fold*** is the result of a fault-propagation fold exposed to increased displacement of the thrust, resulting in the propagation of the fault through the layers. The structure is often associated with drag faults/-folds (Twiss & Moores, 1992, p. 121). A ***salt swell*** is a salt accumulation in response to increased accommodation space and reactivation of salt movement. A ***salt weld*** is the salt gap that forms due to salt dissolution, salt depletion or due to a structural (fault) cut off from the source (Twiss & Moores, 1992, p. 395). ***Coupled*** (or hard-linked) systems consist mainly of thick-skinned faults with a low degree of deformation distribution and a low degree of folding and faulting. ***Decoupled/partially coupled*** (or soft-linked) systems consist mainly of thin-skinned faults with a high degree of deformation distribution and a high degree of folding and faulting (Harvey & Stewart, 1998; Richardson et al., 2005).

3.5 The Bremstein Fault Complex: Seismic Data and Key profiles

In this section the structural setting of the N-S oriented Bremstein Fault Complex (Figures 3-6) will be presented. The general structural setting of the whole study area will be discussed in the next section (section 3.6).

3.5.1 Segmentation of the fault complex

For the purpose of illustrating the altering geometry and structuring of the Bremstein Fault Complex along strike, the study area has been divided into three segments (Chapter 3.1.1 & Figure 3-6). Segment 1, represented by profile I, is located to the south and is characterized by a major ramp-flat-ramp structure (Chapter 3.4). Segment 2, represented by profile V, is the central segment and is characterized by a range of structures: a graben (Chapter 3.4), a relay-ramp (Chapter 3.4), a breached fold (Chapter 3.4) and a drag fault/-fold. Segment 3 is the northern segment, represented by profile XI. This segment consists of a simple geometry, characterized by a single thick-skinned structure accompanied by thin-skinned normal faults.

3.5.2 The fault system

In figures 3-6 & 3-7, the three segments and the positions of the seismic lines crossing those segments are illustrated. The maps also illustrate faults, which are per definition master faults (Chapter 3.4), as well as a few additional faults. Seven faults were interpreted in total, based on their role in the development of the structural geometry of the Bremstein Fault Complex. These faults have been denoted as MFx. Six of these are observed in Segment 1, three in Segment 2 and two in Segment 3. A few antithetic and synthetic accommodation structures were also interpreted adjacent to the master faults, and were labeled NFx (normal fault) or RFx (reverse fault) respectively. Parasitic faults of minuscule size have not been labeled.

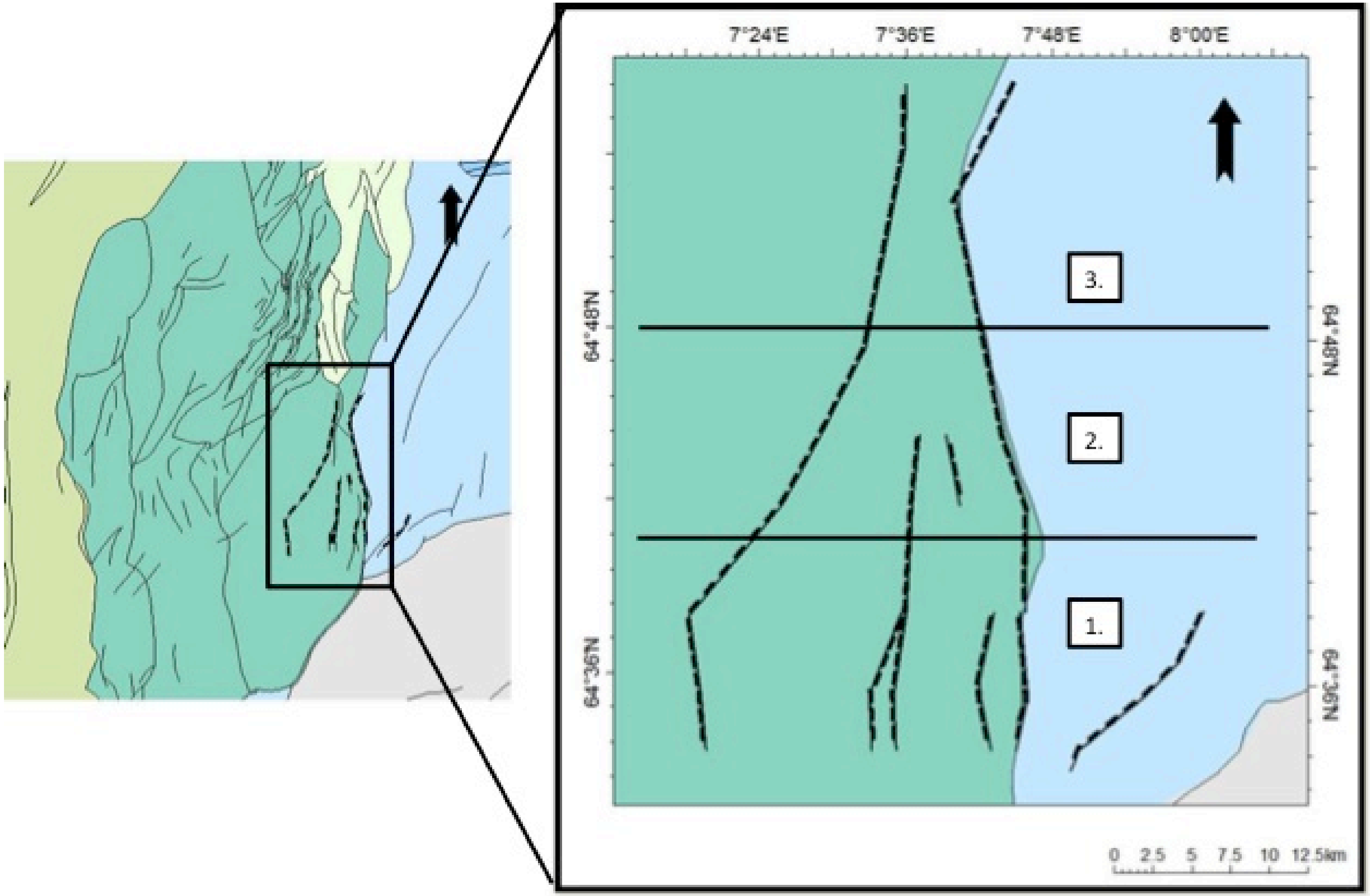


Figure 3-6 Fault map illustrating the master faults interpreted on the in Bremstein Fault Complex, with the Halten Terrace in green located to the west and the Trøndelag Platform in blue to the east. The two solid black lines indicate the segmentation of the study area.

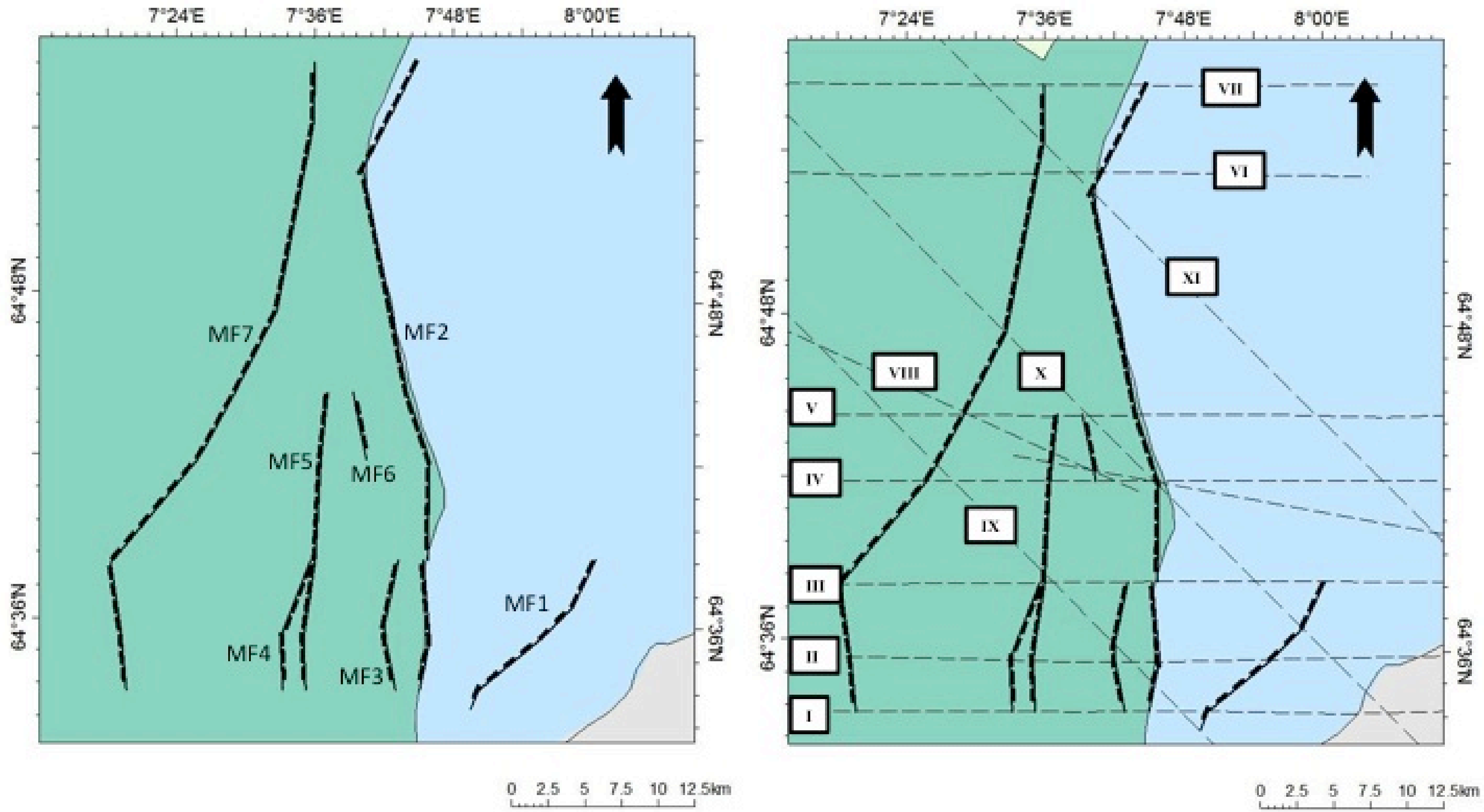


Figure 3-7 Fault maps illustrating the location and name of the seven master faults. Left: Fault names. Right: The seismic lines crossing the individual faults; Profile I (Figure 3-8), Profile V (Figure 3-9), Profile VIII (Figure 3-19), Profile IX (Figure 3-20) and Profile XI (Figure 3-10).

MF1 is the fault located furthest to the east in the study area, on the platform side of the Bremstein Fault Complex (Segment 1, Figure 3-8). It is a listric normal fault (Chapter 3.4) with an NE-SW orientation and with a SW oriented displacement. MF1 extends from the BCU reflection to the lower evaporite layer. It is a thin-skinned fault, penetrating Late Triassic – Jurassic strata. Little or no displacement and/or deformation of the Triassic evaporite layers or the Late Jurassic – Early Cretaceous strata is observed.

MF2 is the eastern most boundary fault on the Halten Terrace (Figure 3-8). It is a (shallow) dipping listric normal fault with a N-S orientation and a SW oriented displacement. The fault is a thin-skinned fault in the south (segments 1 and 2) and a thick-skinned fault in the north (Segment 3). In segments 1 and 2, the MF2 extends from the BCU reflection to the lower evaporite layer, displacing and rotating Late Triassic – Jurassic strata in the hanging-wall. The deformation is especially evident in Segment 2, where MF2 is the western edge of a graben (Chapter 3.4) structure (G2). In Segment 3, MF2 extends into sub-evaporite strata (pre-Middle Triassic), penetrating the evaporite layers. Deformation of strata, fault displacement and presence of Cretaceous onlap is observed. MF2 has been mentioned in a few previous publications. In a publication by Elliott et al. (2012) MF2 is referred to as fault A. The fault is also mentioned in a publication by Wilson et al. (2013) where MF2 is without any formal name, but described as a strong listric normal fault.

MF3 is located in the middle of the Bremstein Fault Complex (Segment 1, Figure 3-8), bounding the eastern side of a graben structure (G1). MF3 is a normal fault with a NNE-SSE orientation and with a SW displacement. The fault is thin-skinned, extending from the BCU reflection to the upper evaporite layer, penetrating Late Triassic to Jurassic strata. Large displacement and rotation is observed in the hanging-wall, as well as Cretaceous onlap on the footwall. The fault is also accompanied by antithetic fault on the hanging-wall side.

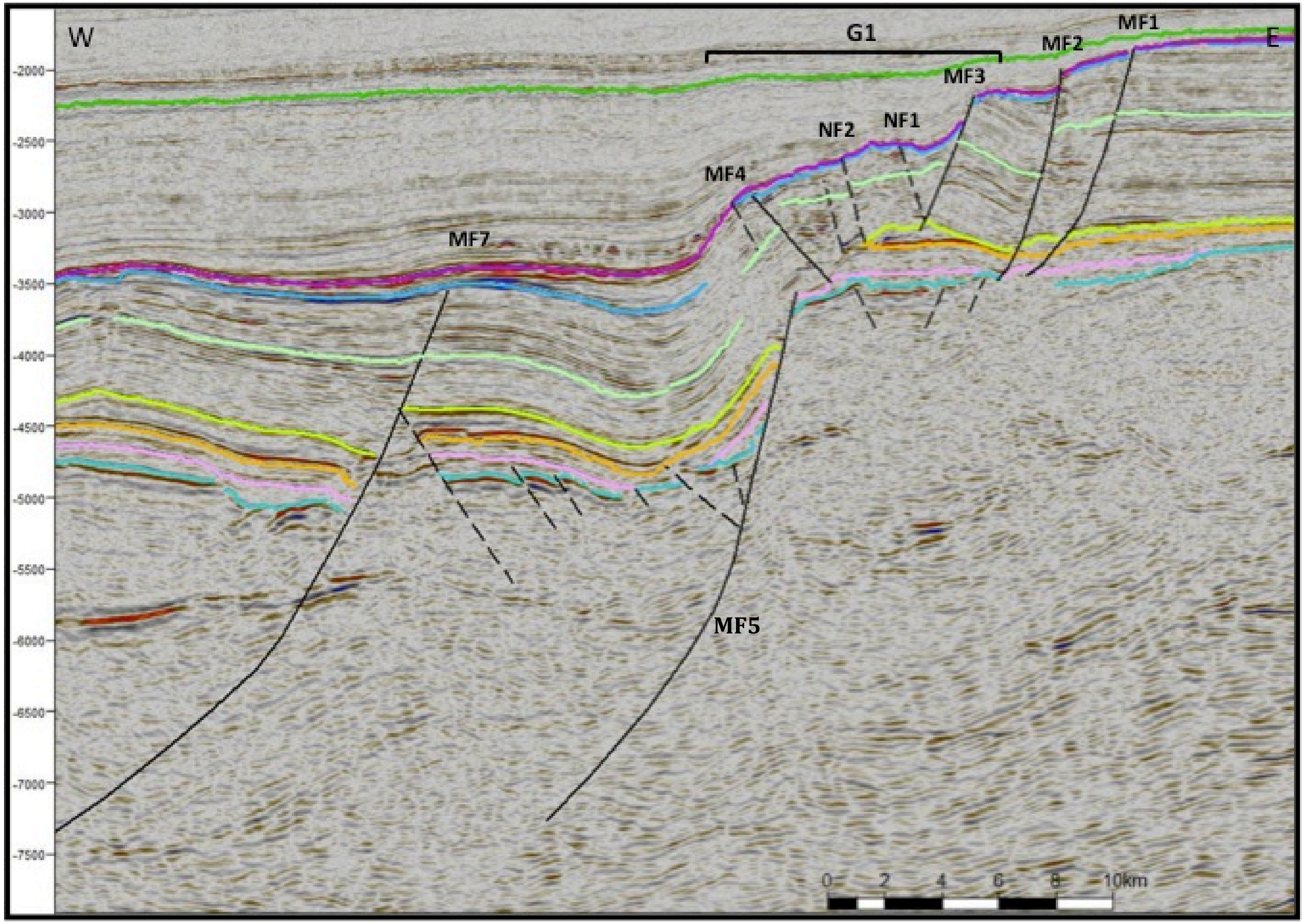


Figure 3-8 Interpretation of profile I. The location of the seismic line can be seen in Figure 3-7 and the color-coding of the seismic lines can be seen in Figure 3-5.

MF4 is located down-dip from the previously mentioned faults, on the western side of the Bremstein Fault Complex (Segment 1, Figure 3-8). MF4 is the western boundary fault to G1, with a NNW-SSE orientation and eastern dip. The fault is a thin-skinned reverse fault, extending from the BCU reflection to the lower evaporite layer, penetrating heavily rotated Late Triassic to Jurassic strata. Cretaceous onlap is observed on the hanging-wall side.

MF5 is the fault located furthest to the west in the Bremstein Fault Complex. MF5 is a thick-skinned, blind fault with a N-S orientation and a NE oriented displacement. The fault extends from Late Paleozoic strata to the lower (possible upper) evaporite layer in Segment 1 (Figure 3-8). In Segment 2, MF5 extends into Jurassic strata, piercing the evaporite layers (Figure 3-9). The fault is responsible for a range of thrust structures on the Bremstein Fault Complex: fault-propagation-fold, breached-fault and drag fault/-fold (Chapter 3.4). Accommodation structures formed in response to the fault activity are visible in the adjacent strata e.g. folding (syncline and anticline structures), bending and drag structures.

MF6 is located on the western side of the Bremstein Fault Complex, bounding the western side of G2 (Segment 2, Figure 3-9). MF6 is a thin-skinned normal fault, with a NNW-SSE orientation and with a SE oriented displacement. The fault extends from the BCU reflection to the upper evaporite layer, rotating the strata within the graben and displacing salt at the base. Early Cretaceous onlap is evident on the hanging-wall side, a wedge-shaped sequence is visible on top of the structure and a varying amount of vertical offset with depth is clear, i.e. the older strata have larger offset than the younger. Faults are observed between the sub-horizontal evaporite layers and the close to horizontal Top Åre Formation strata. Onlap, Cretaceous wedge-deposits and fault displacement of the base Cretaceous reflection is also evident.

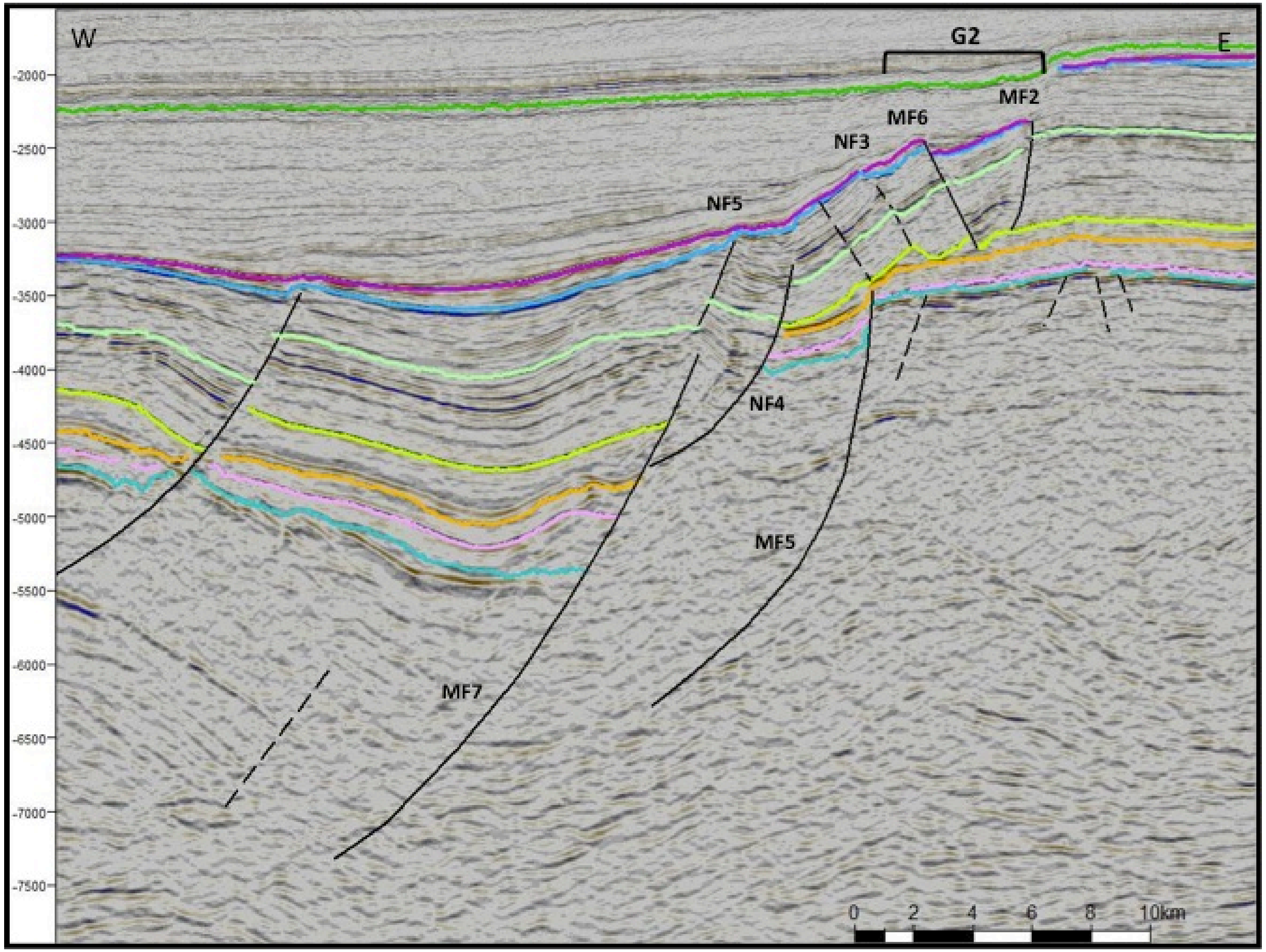


Figure 3-9 Interpretation of profile V. The location of the seismic line can be seen in Figure 3-1 and the color-coding for the seismic reflectors can be seen in Figure 3-5.

MF7 is the fault located furthest to the west, on the terrace side of the Bremstein Fault Complex. MF7 is both a thick-skinned and thin-skinned normal fault, with a N-S to NE-SW orientation and a SW oriented displacement. The fault extends from Late Paleozoic strata to the top Garn Formation reflection in segments 1 and 2. In Segment 3, MF7 extends from late-middle Triassic strata to Early Cretaceous strata (Figure 3-10). In all of the segments the fault penetrates, dislodges and rotates the evaporite layers. An overall difference in rotation and deformation is also evident, between the lower and upper strata, as well as displacement of both the base Cretaceous and the top Garn Formation reflections. MF7 has previously been mentioned in a publication by Wilson et al. (2013), where the fault is referred to as fault A.

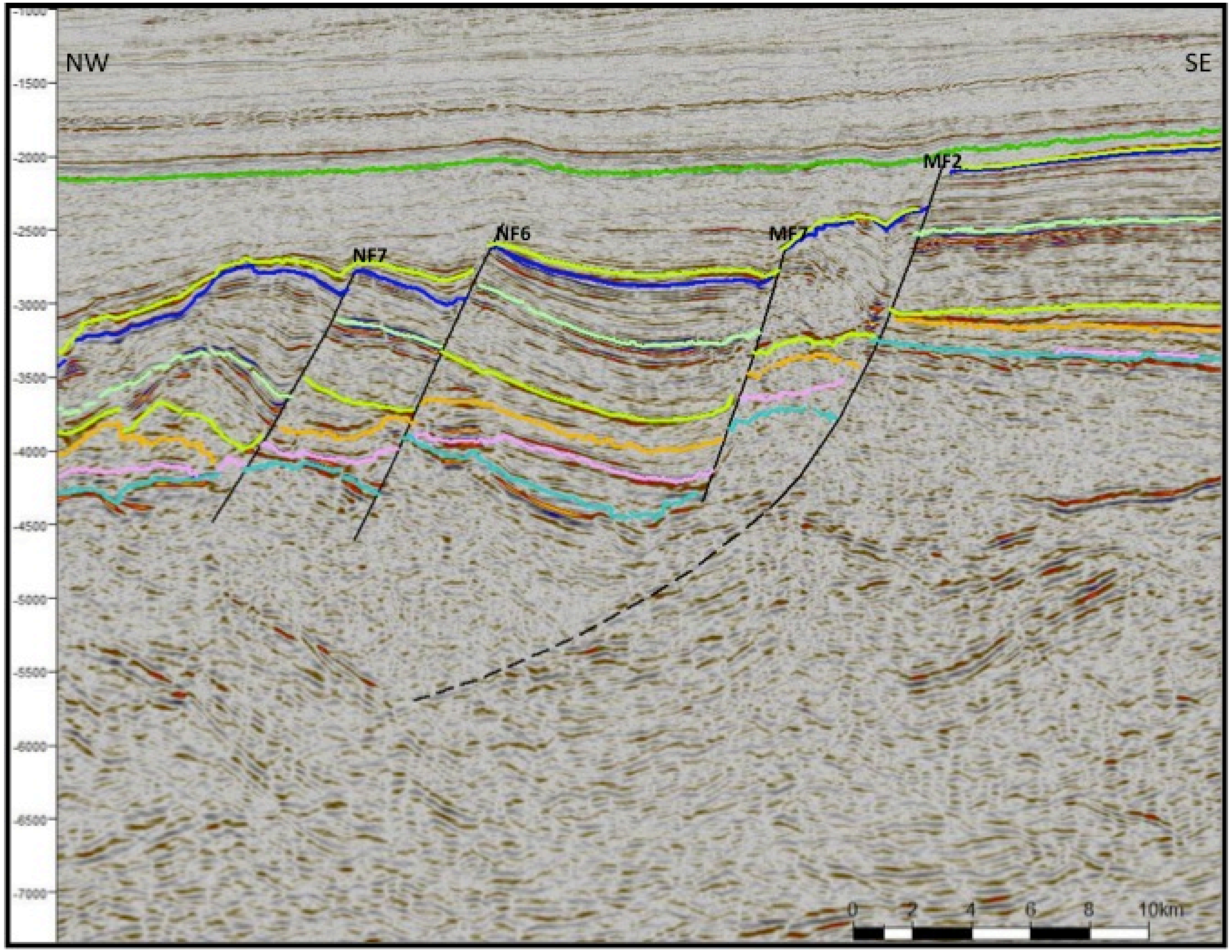


Figure 3-10 Interpretation of profile XI. The location of the seismic line can be seen in Figure 3-1 and the color-coding for the seismic reflectors can be seen in Figure 3-5.

3.5.3 Segment 1

Figure 3-6 illustrates the location of Segment 1. It is the longest of the three segments and is represented by four 2D seismic lines (Figure 3-7). Profiles I, II and III are oriented E-W, while Profile IX is oriented NW-SE. Profile I (Figure 3-8) oriented E-W, was chosen to represent this segment. It is the first seismic profile (within the scope of the study) that crosses the Bremstein Fault Complex.

Nine out of the ten reflections mentioned above (Chapter 3.2, Figure 3-2), were interpreted in Profile I (Figure 3-8). The reflection defined as the base of the Cenozoic (Chapter 3.2) is continuous and unaffected by the major faults. The reflections defined as the base of the Cretaceous, the top of the Garn Formation and the top of the Åre Formation (Chapter 3.2) are displaced by faults with a SW displacement, on the eastern side of the Bremstein Fault Complex. On the western side, little fault displacement is observed above the evaporite layers. The evaporite reflections are displaced and/or deformed by faults throughout the profile. The deepest reflection interpreted in Profile I is the top Permian reflection (Chapter 3.2 & Figure 3-8). Thick-skinned faults cut and displace the reflection on the western side, while on the eastern side the reflection could not be traced due to poor resolution of the data. A total of five master faults were interpreted in Profile I: MF1, MF2, MF3, MF4 and MF5 (Chapter 3.5.2, Figure 3-7).

The main structure in Segment 1 is the ***ramp-flat-ramp*** structure located in the middle of the Bremstein Fault Complex (Figure 3-11). The upper ramp segment is portrayed by the listric master fault MF1 (Chapter 3.5.2, Figure 3-7), with an NE-SW orientation and with a SW displacement. MF1 is located on the easternmost side of the Bremstein Fault Complex, bounding the Trøndelag Platform. The lower ramp segment is portrayed by the blind master fault MF5 (Chapter 3.5.2, Figure 3-7), with a N-S orientation and with a SW displacement. MF5 is located on the westernmost side of the Bremstein Fault Complex, bounding the Halten Terrace. A horizontal lower evaporite layer, a thick upper evaporite layer (salt swell) and a cover of rotated Upper Triassic – Jurassic strata, characterize the flat portion of the ramp-flat-ramp structure. In total the structure is about 9 km wide (the flat portion is measured to about 6 km), with a stepwise western dip. Vertically the structure penetrates strata from the top of the Permian to the base of the Cretaceous. The presence of a ramp-flat structure in a normal fault system, is in accordance to observations made in similar settings by Harvey and Stewart (1998).

In the section above, a ***salt swell*** structure was mentioned in regards to the flat portion of the ramp-flat-ramp, and in the fault section (Chapter 3.5.2) a drag fault and a syncline was presented in association with the MF5 master fault. These are secondary structures or accommodation structures, to the ramp-flat-ramp. The salt swell is located between master faults MF2 and MF4 in Profile I (Figure 3-12, A) and bounded by MF3 in Profile IX (Figure 3-12, B). The salt structure can be characterized as a salt dome, while the overlying strata can be termed an anticline, due to the variation in dip from east to west and the presence of older strata (Triassic evaporites) on the concave side and younger strata (Early Cretaceous) on the convex side. Furthermore, the SE dip of the top Åre Formation reflection and the NE dip of the BCU reflection, adjacent to MF3 (Figure 3-12, B), indicate downwarping. Thus the structure can also be termed a ***rollover anticline***. Figure 3-13 illustrates both the ***drag fault/-fold*** and the ***syncline*** structures. The drag fault structure is located in the MF5 hanging-wall, and was discussed in Chapter 3.5.2. The hanging-wall syncline structure is located between master faults MF5 and MF7. The structure is evident by the folding of the Jurassic strata on the concave side of the bedding surface and the Triassic evaporites on the convex side.

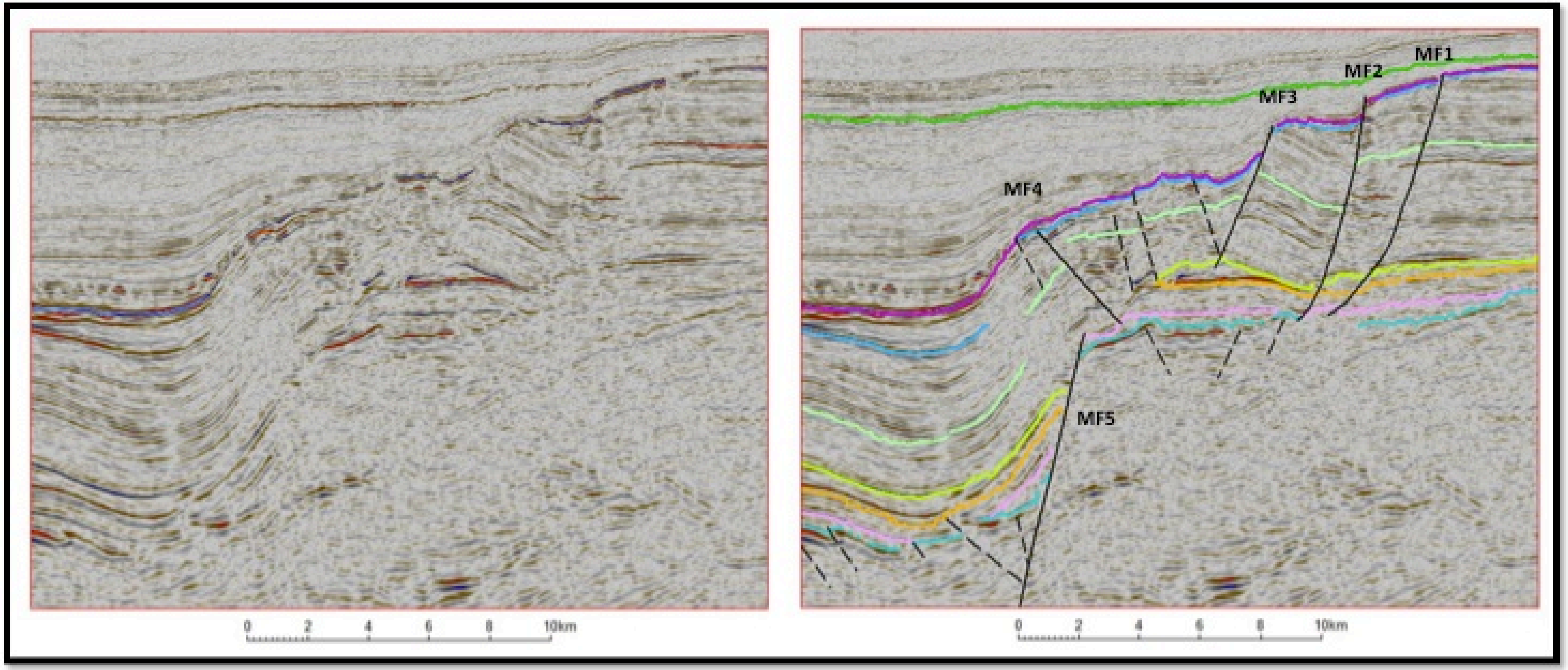


Figure 3-11 A close-up of the ramp-flat-ramp structure seen in profile I (Figure 3-8). Left: The structure illustrated without reflection and fault interpretations. Right: The structure illustrated with interpretation of the reflections and faults. The color-coding for the reflections can be seen in Figure 3-5.

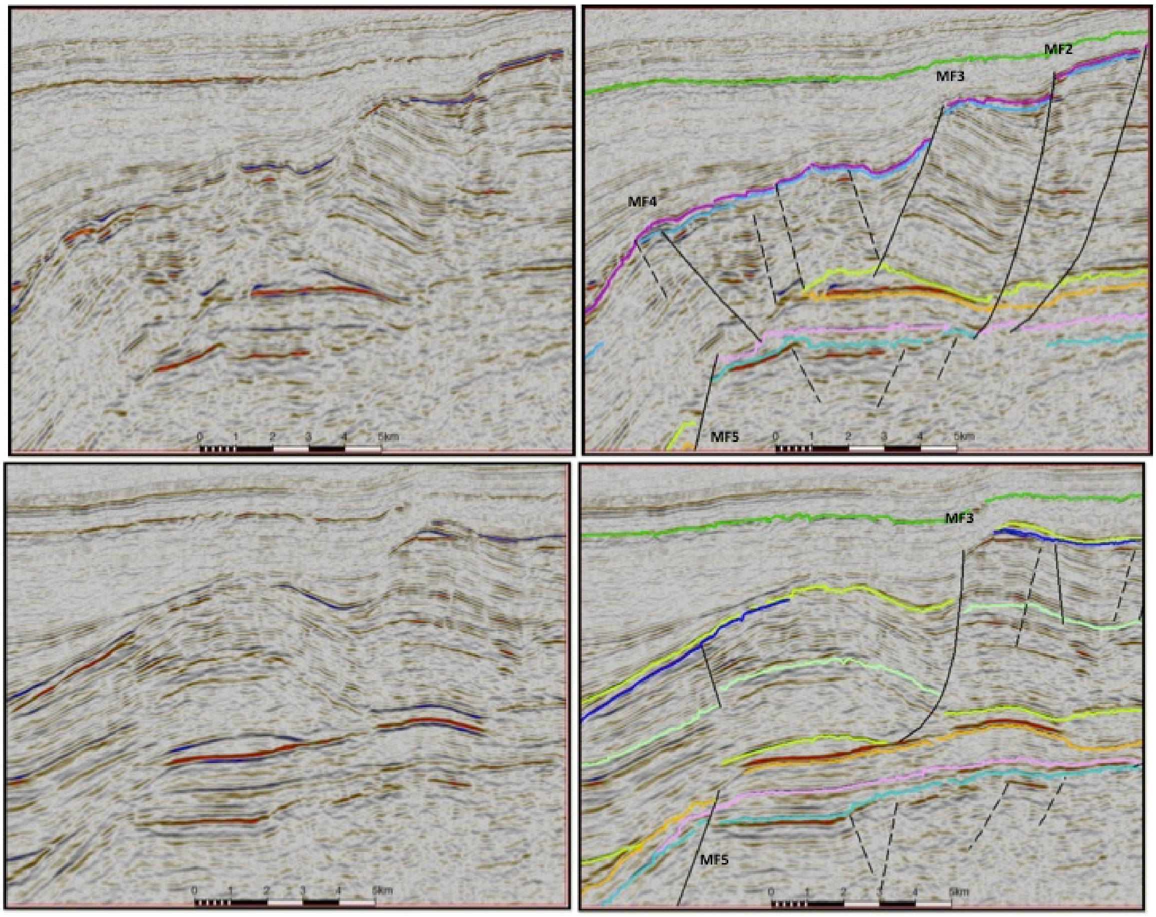


Figure 3-12 A close-up of the rollover anticline structure seen in profiles I (Figure 3-8) and IX; A and B. Left: The structures illustrated without reflection and fault interpretations. Right: The structures illustrated with interpretation of the reflections and faults. The color-coding for the reflections can be seen in Figure 3-5.

3.5.4 Segment 2

Figure 3-6 illustrates the location of Segment 2. It is the middle segment and is represented by three 2D seismic lines (Figure 3-7). Profiles IV and V are oriented E-W, while Profile X is oriented NW-SE. Profile V (Figure 3-9) oriented E-W, was chosen to represent this segment.

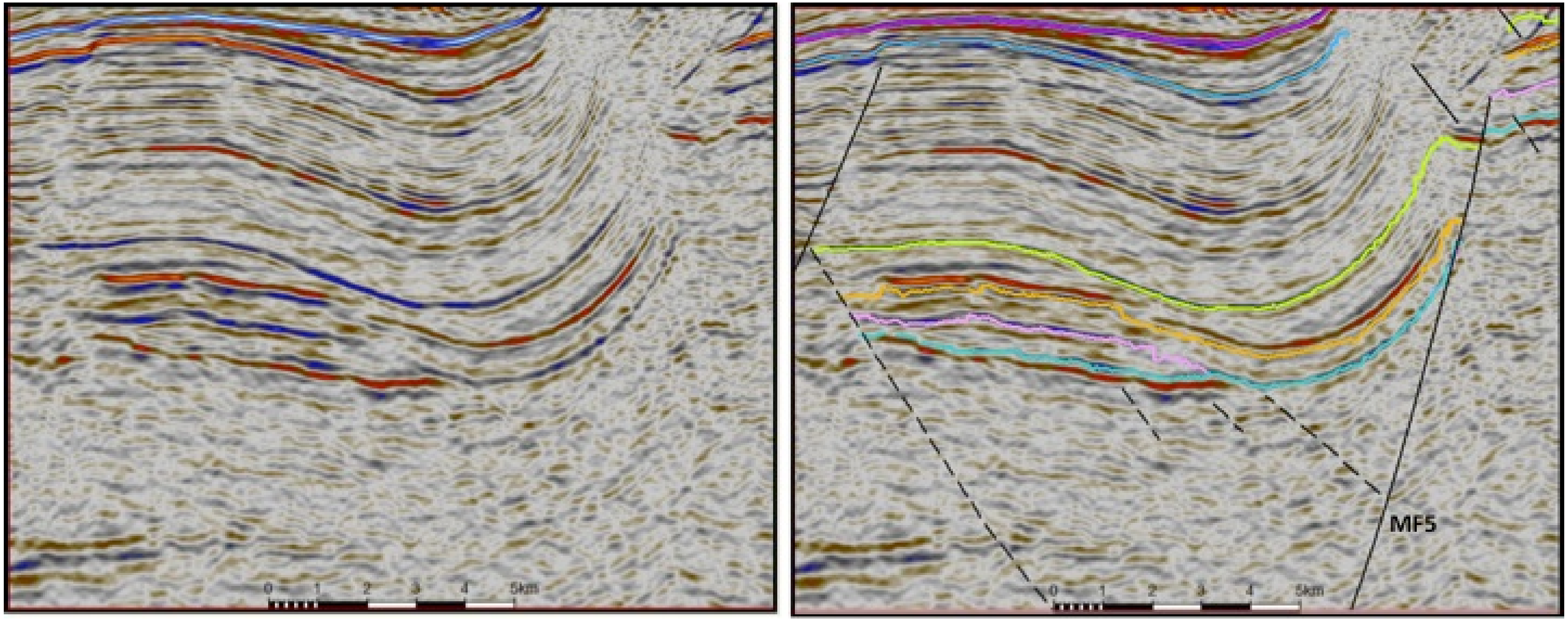


Figure 3-13 A close-up of the drag fault and the hanging-wall syncline found in profile II. Left: The structure illustrated without reflection and fault interpretations. Right: The structure illustrated with interpretation of the reflections and faults. The color-coding for the reflections can be seen in Figure 3-5.

Nine out of the ten reflections presented earlier (Chapter 3.2, Figure 3-2), were interpreted in Profile V (Figure 3-9). The reflection defining the base Cenozoic (Chapter 3.2) is continuous, with exception to one area on the eastern side, affiliated with the Bremstein Fault Complex. The reflections defined as the base of the Cretaceous, the top of the Garn Formation and the top of the Åre Formation (Chapter 3.2) are horizontal and continues on both the Trøndelag Platform border and close to the Halten Terrace area. In the Bremstein Fault Complex the reflections have a southwestern dip. The four evaporite reflections are sub-horizontal throughout the profile, with few discontinuities. The deepest reflection interpreted in Profile V was the top Permian reflection (Chapter 3.2). The reflection is heavily curved and discontinuous. A total of four master faults were interpreted in Profile V: MF2, MF5, MF6 and MF7 (Chapter 3.5.2, Figure 3-7).

The ***graben*** structure previously introduced as G2 (Chapter 3.5.2) is illustrated in Figure 3-14. The structure is located on the easternmost side of the Bremstein Fault Complex, between the conjugate master faults MF2 and MF6 (Figure 3-8). MF2 is a shallow dipping listric normal fault with an N-S orientation and with a SW displacement (Chapter 3.5.3, Figure 3-7). MF6 is a shallow dipping listric normal fault, with a NNW-SSE orientation and with a SE displacement (Chapter 3.5.3, Figure 3-7). In Figure 3-14A, the graben structure is accompanied by a synthetic fault (NF3) on the western side and basal salt swells (Chapter 3.4). The salt swells are observed in both the hanging-wall of NF3 and MF6. The interior of the structure is tilted towards the SW, with little or no displacement of the seismic reflections. In Figure 3-14B, the graben structure is accompanied by both salt swell and salt weld (Chapter 3.4) structures. The salt swell structures are observed in the footwall block of both MF2 and MF6. The salt weld is observed in the middle of the graben. Heavily rotated strata with southwestern dip characterize the interior of the structure. Wedge-shaped Cretaceous strata on top of the structure, is also evident. Two previous publications have illustrated and discussed the graben structure from Segment 2 (Elliott et al., 2012; Wilson et al., 2013).

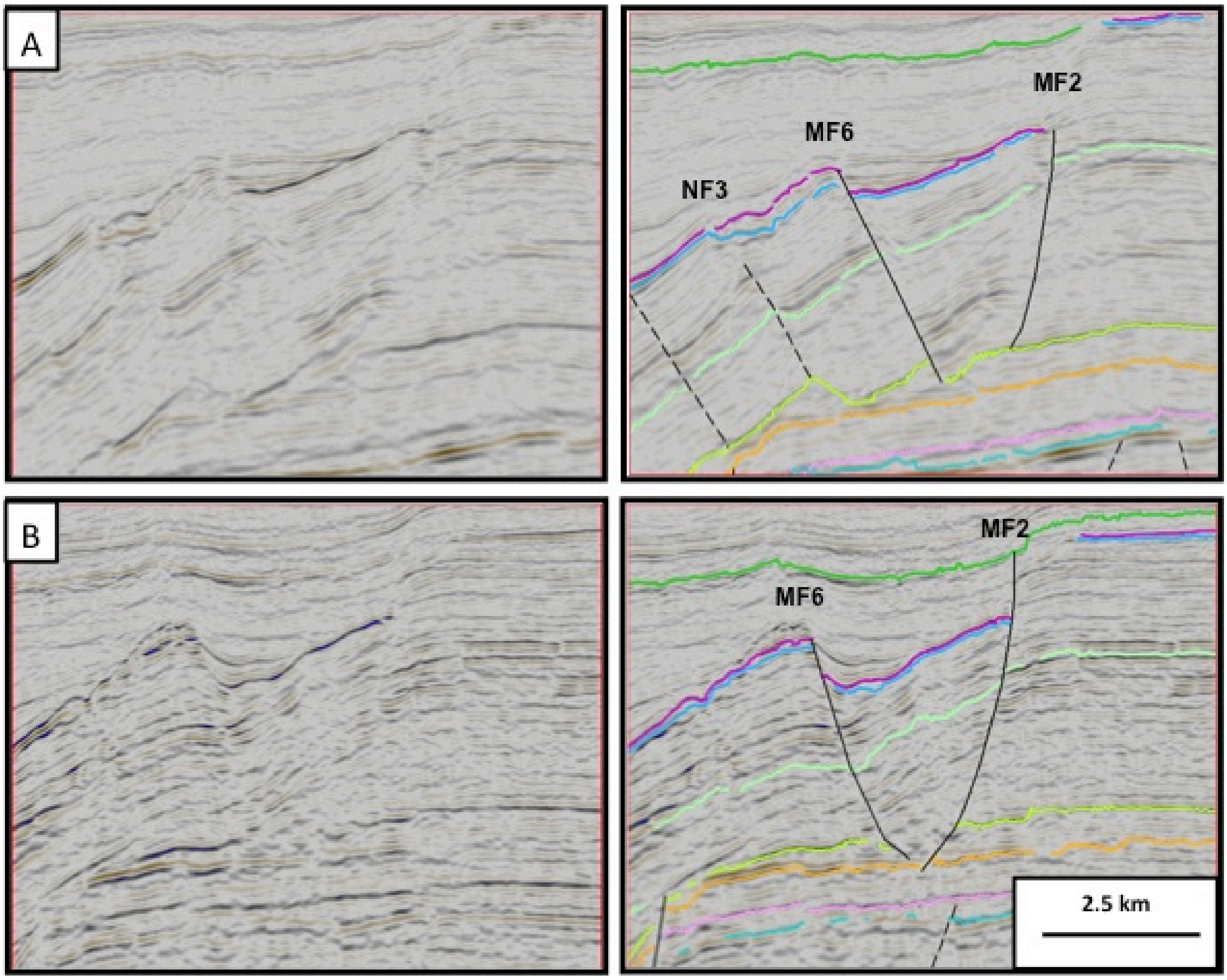


Figure 3-14 A close-up of the G2 structure accompanied by basal salt swells (A) and a salt weld (B) from profiles V (Figure 3-9) and IV. Left: The structures illustrated without reflection and fault interpretations. Right: The structures illustrated with interpretation of the reflections and faults.

Graben systems are often associated with ***relay-ramp*** structures (Chapter 3.4, Figure 3-15). A relay-ramp structure is located on the Halten Terrace side of the Bremstein Fault Complex, between master fault MF5 and NF4, a synthetic normal fault (Figure 3-9). MF5 is a hard-linked, blind fault with a N-S orientation and NE oriented displacement. NF4 is a shallow dipping normal fault with a SW oriented displacement. The interior of the structure consists of folded evaporite layers covered by sub-horizontal Jurassic strata, evident by the sub-horizontal top of the Åre Formation reflection. According to Peacock and Sanderson (1994) relay-ramps or transfer zones are to be expected in normal fault systems, where they function as links between areas of complex deformation.

West of the relay-ramp, on the Halten Terrace side of the Bremstein Fault Complex, a ***breached fold*** is visible (Chapter 3.4, Figures 3-9 & 3-16). The structure is located at the fault tip of master fault MF5, adjacent to the synthetic normal fault NF4. MF5 is a hard-linked, blind fault with a N-S orientation and a NE oriented displacement (Chapter 3.5.2). This is indicating that the structure may originally have been a fault-propagation-fold, exposed to increased thrust, resulting in the breaching of the fold and thus the formation of the breached fold structure. Adjacent structures like a ***drag fault/-fold*** and a hanging-wall ***syncline*** accentuate this hypothesis. The hanging-wall of master fault MF5 is illustrated in Figure 3-17, with the drag fault/-fold and syncline located close to MF5. The NE drag of the reflections close to the master fault and the bending of the layers indicate fault activity from at least the Early-Middle Triassic (pre-evaporite deposition). A new configuration can also be seen in association with the syncline structure, a possible older tectonic trend. The lower layers in the syncline can be characterized as curved and folded, while the upper layers are sub-horizontal, indicating deposited into a preset accommodation space (Figure 3-17). These observations are in accordance with previously publications discussing the presence of fault-penetrating folds and breached folds (forced folds) on the Halten Terrace, among them Withjack et al. (1989); Withjack and Callaway (2000) and Withjack et al. (1989).

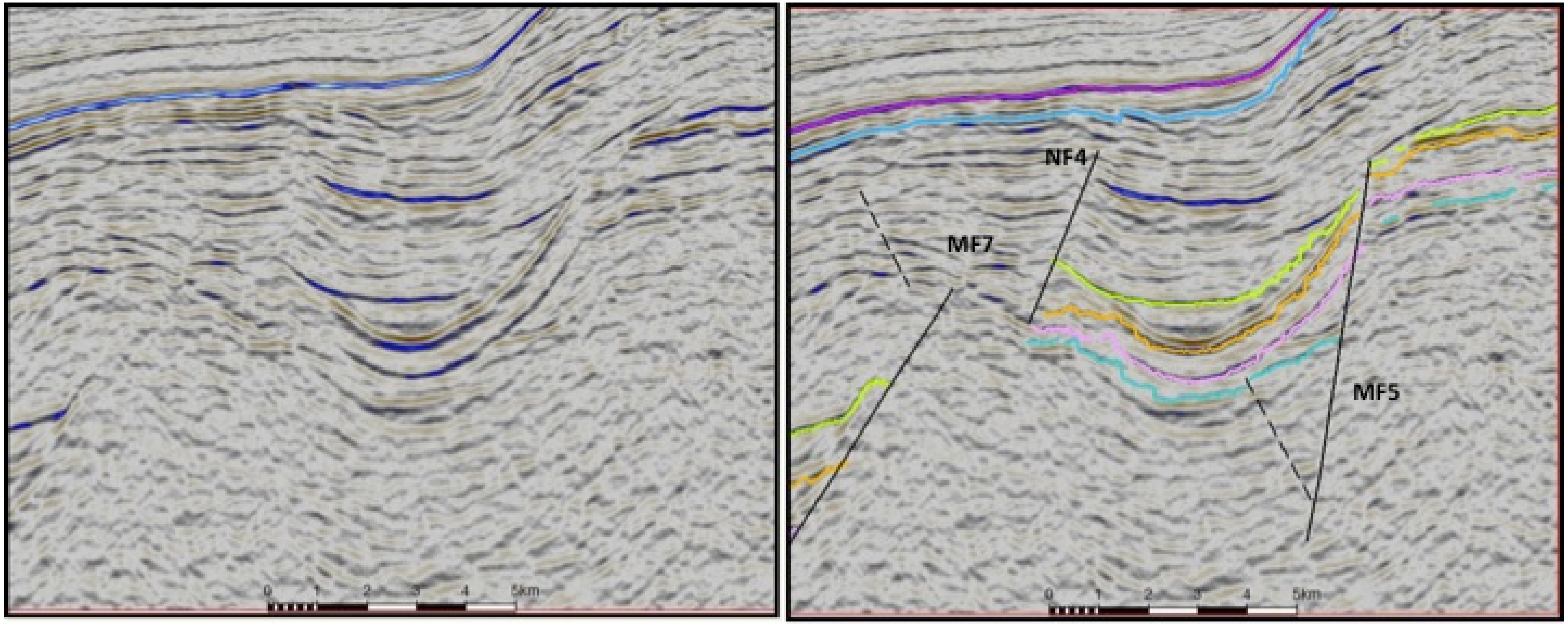


Figure 3-15 A close-up of the relay-ramp structure found in profile IV. Left: The structure illustrated without reflection and fault interpretations. Right: The structure illustrated with interpretation of the reflections and faults.

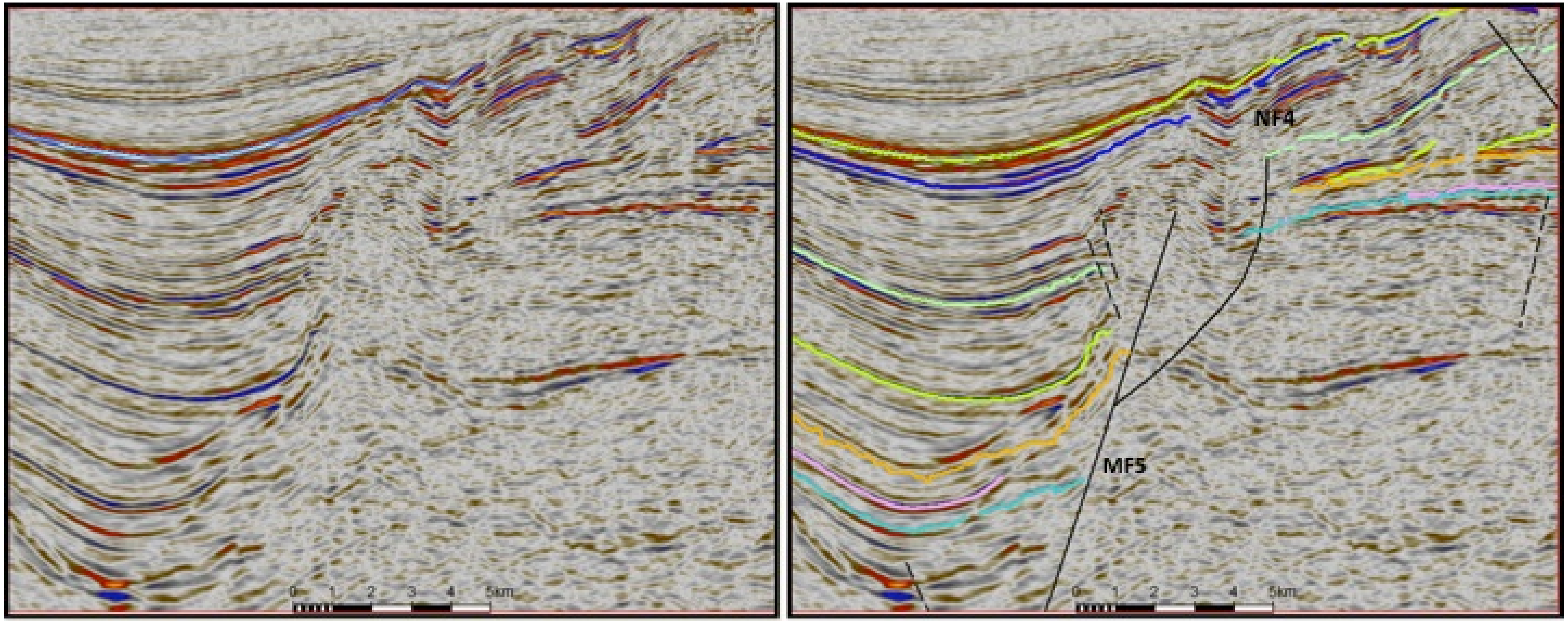


Figure 3-16 A close-up of the breached-fold structure seen in profile X. Left: The structure illustrated without reflection and fault interpretations. Right: The structure illustrated with interpretation of the reflections and faults.

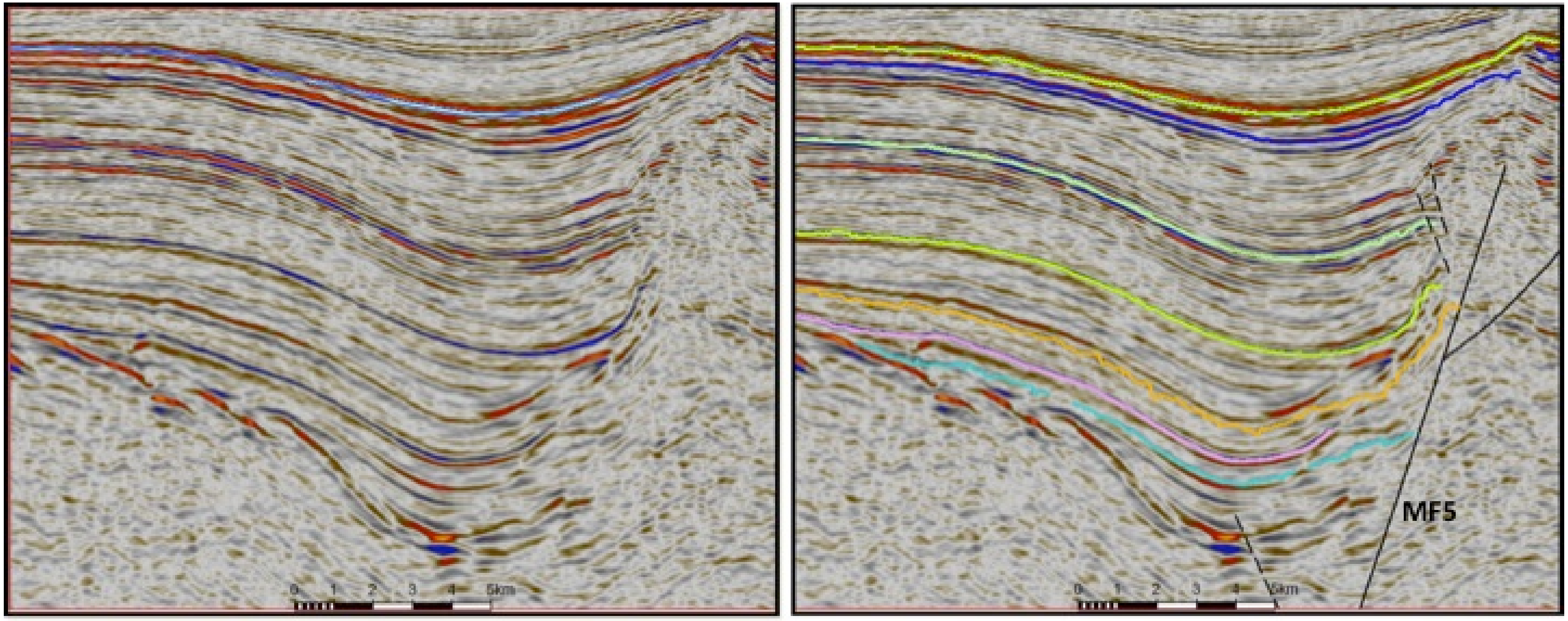


Figure 3-17 A close-up of the secondary structures; drag fault/-fold and hanging-wall syncline found in profile X. Left: The structure illustrated without reflection and fault interpretations. Right: The structure illustrated with interpretation of the reflections and faults.

3.5.5 Segment 3

Figure 3-6 illustrates the location of Segment 3. It is the northern segment and is represented by three 2D seismic lines (Figure 3-7). Profiles VI and VII are oriented E-W, while Profile XI is oriented NW-SE. Profile XI (Figure 3-10) oriented NW-SE, was chosen to represent this segment.

Nine out of the ten reflections discussed above (Chapter 3.2, Figure 3-2), were interpreted in Profile XI (Figure 3-17). The reflection defined as the base of the Cenozoic (Chapter 3.2) is sub-horizontal and continuous throughout the profile. The reflections defined as the base of the Cretaceous, the top of the Garn Formation and the top of the Åre Formation (Chapter 3.2) are sub-horizontal and displaced by normal faults with a SW displacement. The four evaporite reflectors are all horizontal. The deepest reflection interpreted in Profile XI is the top Permian reflection (Chapter 3.2). However, only a minor part of the reflection was interpreted due to the poor resolution of the data. A total of two master faults were interpreted: MF2 and MF7 (Chapter 3.5.2, Figure 3-7).

The main structure in Segment 3 is a steeply dipping listric fault, previously introduced in Chapter 3.5.2. The structure is located in the middle of Profile XI (Figure 3-10). MF2 has a N-S orientation and SW oriented displacement, while MF7 has a N-S to NE-SW orientation and SW oriented displacement. The area located between the master faults can be characterized as extensively deformed. The lower sedimentary units, the Triassic evaporites, have a southwestern dip and drag along MF2, while the Late Triassic-Jurassic layers have a southeastern dip and drag along MF7. This might possibly indicate several periods of fault activity, as well as an indication of differential fault activity. Two publications have previously discussed the structures found in the northern part of the Bremstein Fault Complex (Osmundsen & Ebbing, 2008; Wilson et al., 2013).

3.6 The regional study: Seismic Data and Key profiles

In this section, the overall structural trends within the study area are presented, with the use of a time-structure map and key profiles. The time-structure map (Figure 3-18) illustrates the entire study area at the base Cretaceous horizon, whilst the key profiles cross the study area, extending from the Halten Terrace across the Bremstein Fault Complex to the Trøndelag Platform.

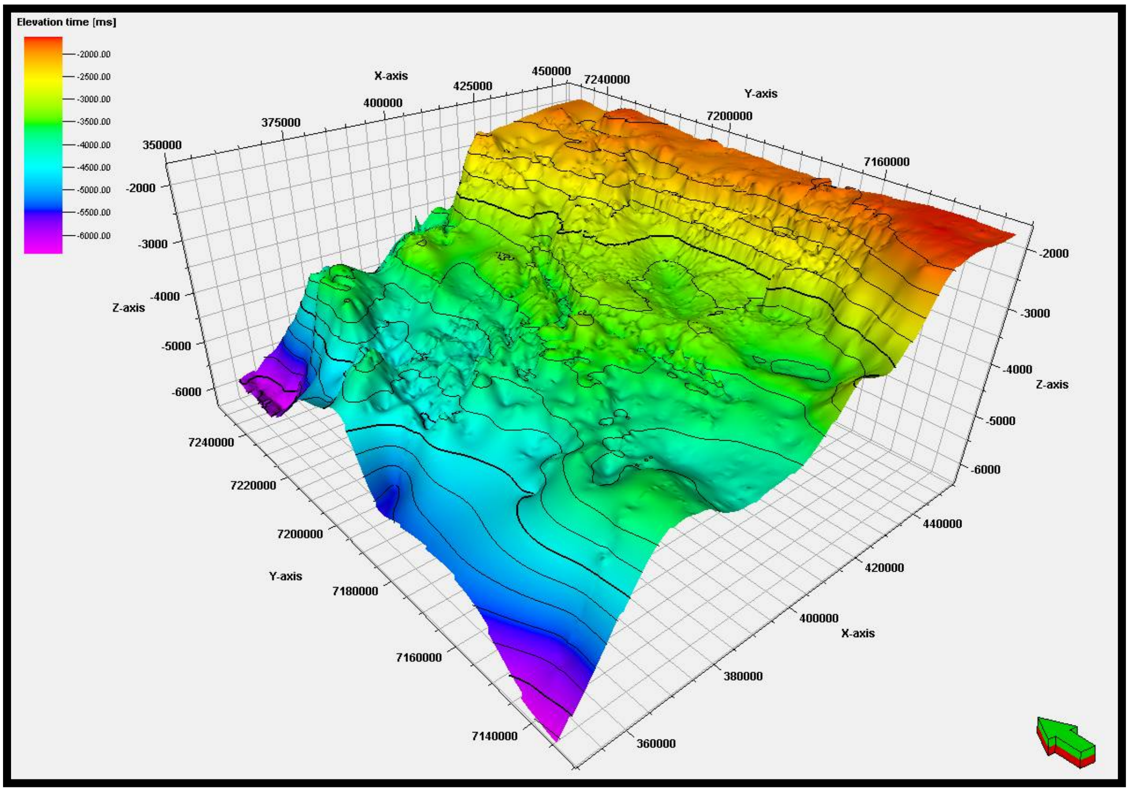


Figure 3-18 The time-structure map of the base of the Cretaceous. The arrow points north and the color-coding illustrates depth in two-way-time.

3.6.1 Time-structure map

In Figure 3-18 the time-structure map is presented, with an illustration of the depth relations existing in the study area. On the Trøndelag Platform (the far eastern side) the horizon is sub-horizontal, with a depth of about 1-2 s TWT. A slight decrease in depth can be seen in the northern and southern corners of the grid, corresponding with the Nordland Ridge and the Vingleia Fault Complex, respectively. In the Bremstein Fault Complex the horizon has a sharp dip, with a distinct drop in depth to about 4 s

TWT. The drop is more distinct in the south than in the north, due to a basin located in the hanging-wall. The basin corresponds to the previously discussed syncline structures (Segments 1 and 2, Chapters 3.5.3/4). Throughout the Halten Terrace the horizon is predominantly undulant, with depths between 3,5-4,5 s TWT. On the far western side, the horizon dips even further corresponding with the location of the Rås Basin.

3.6.2 Key profiles and reflections

Two profiles introduced in chapter 3.3.1, were chosen for the overall structural trend analysis. Profile VIII (Figure 3-19) oriented NNW-SSE and profile IX (Figure 3-20) oriented NW-SE (Figure 3-1).

Nine reflections (Chapter 3.2, Figure 3-2) were interpreted in Profile VIII (Figure 3-19) and ten in Profile IX (Figure 3-20). The reflection defined as the base of the Cenozoic (Chapter 3.2) is a continuous sub-horizontal reflection, unaffected by the major faults in both profiles. The reflections defined as the base of the Cretaceous and top of the Garn Formation (Chapter 3.2), are undulant, with several fault discontinuities throughout the profiles. The top of the Åre Formation reflection is only interpreted on the western side of both profiles, due to poor resolution of the data and fault discontinuities. The evaporite reflections have been mapped continuously, exhibiting displacement and/or deformetion by faults throughout. The deepest reflection interpreted in Profile VIII is the top Permian reflection (Chapter 3.2). The reflection has not been mapped continuously due to the presence of several fault discontinuities and the poor resolution of the data at depth. In Profile IX the Permian reflection is of similar quality. The deepest reflection mapped in Profile IX is presumed to be a basement reflection. The reflection is only visible on the far eastern side below the Trøndelag Platform.

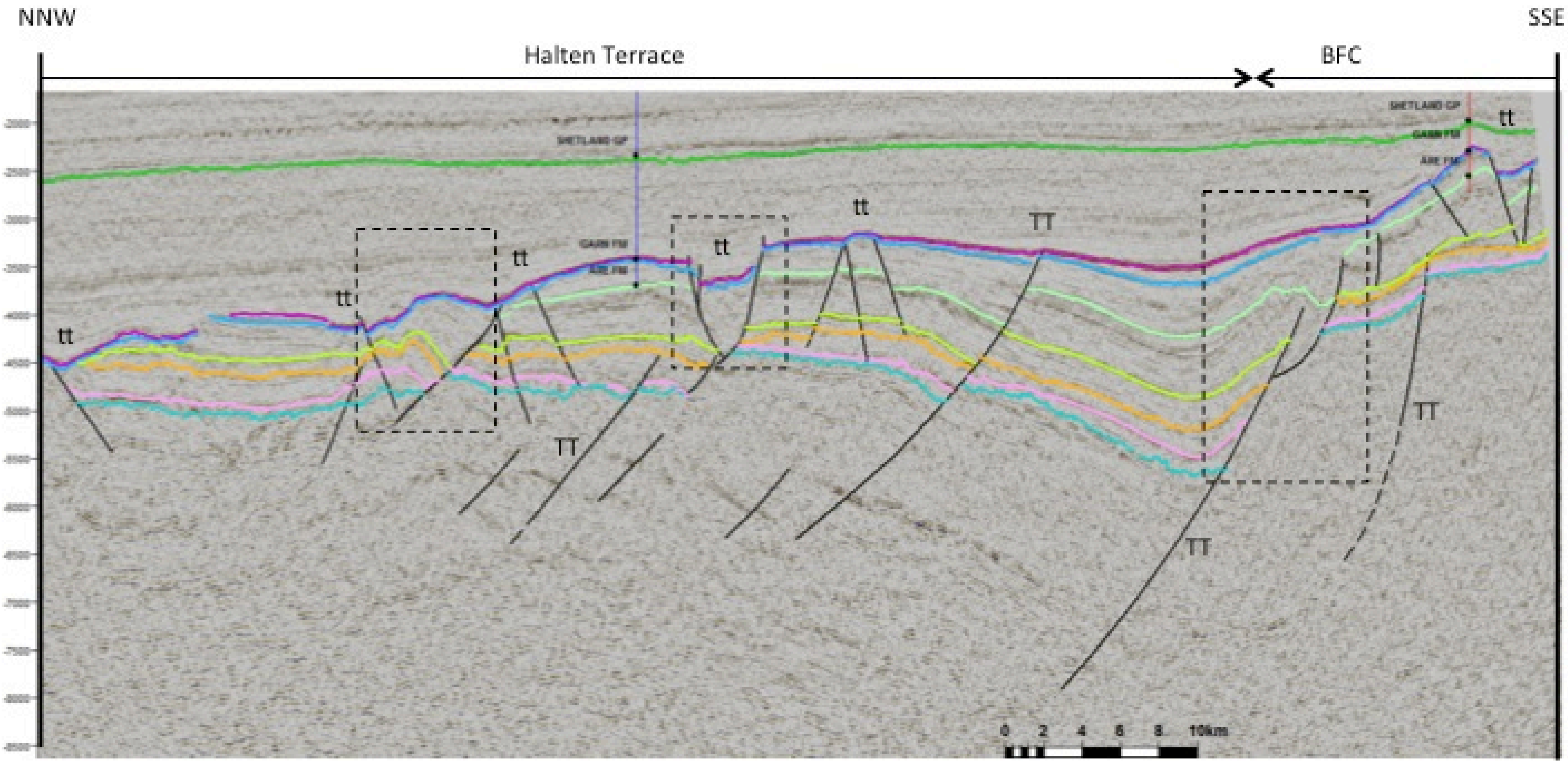


Figure 3-19a Interpretation of the western side of Profile VIII. Thick- and thin-skinned faults have been denoted TT and tt and special structures are indicated by a stippled black box. The location of the seismic line can be seen in Figure 3-1 and the color-coding for the seismic reflectors can be seen in Figure 3-2.

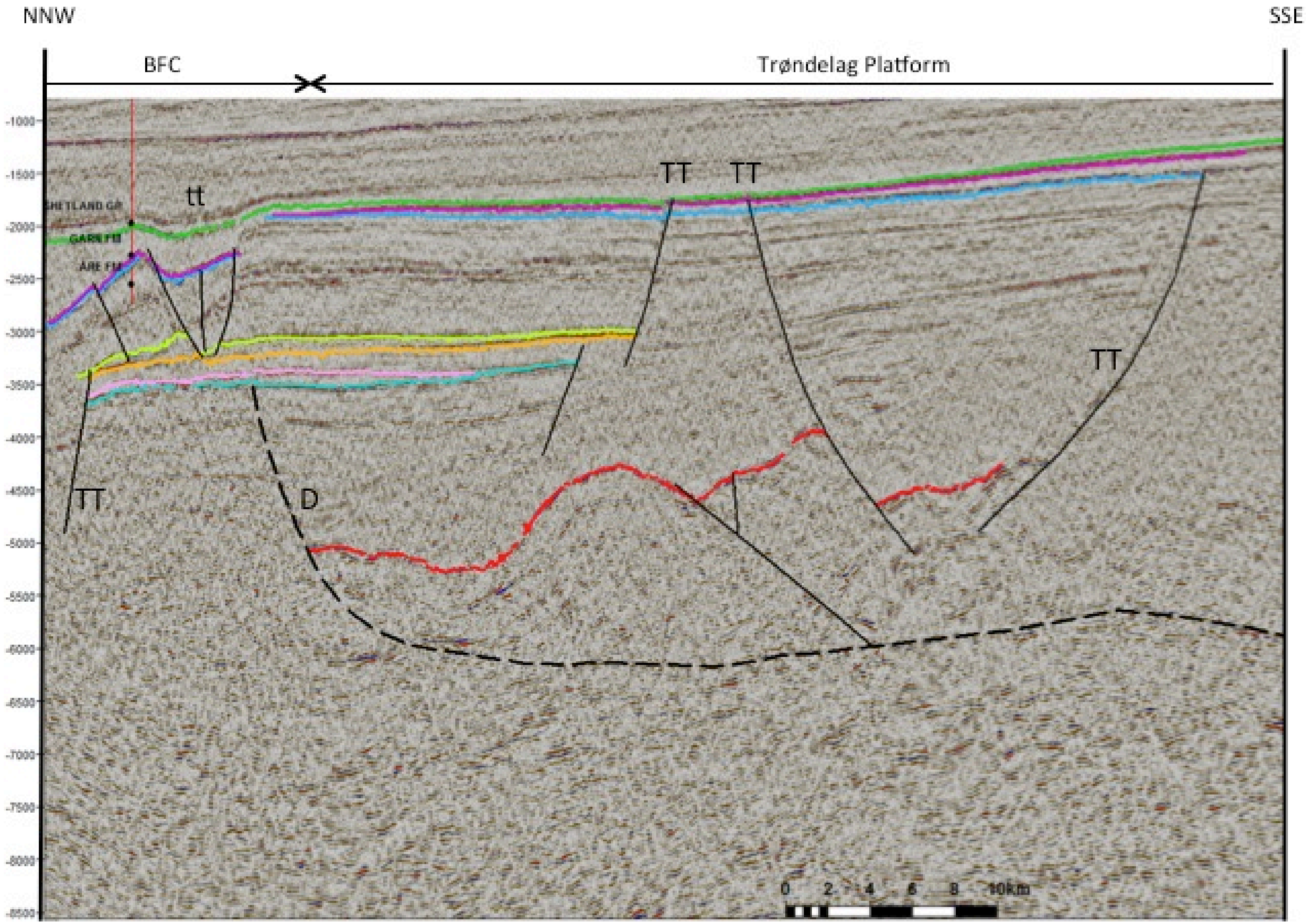


Figure 3-19b Interpretation of the western side of Profile VIII. Thick- and thin-skinned faults have been denoted TT and tt, detachments are stippled and denoted D and special structures are indicated by a stippled black box. The location of the seismic line can be seen in Figure 3-1 and the color-coding for the seismic reflectors can be seen in Figure 3-2.

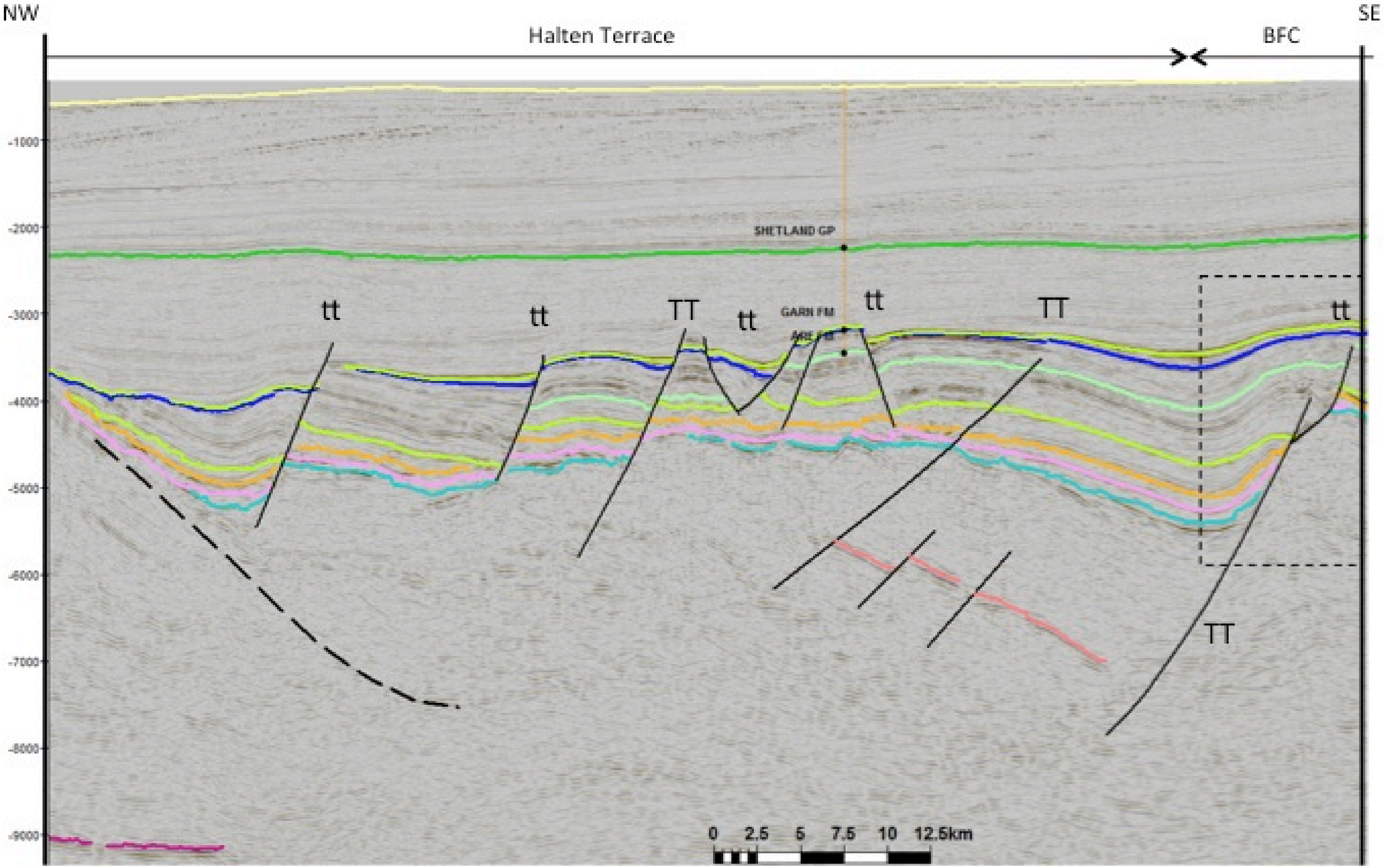


Figure 3-20a Interpretation of profile IX. Thick- and thin-skinned faults have been denoted TT and tt, detachments are stippled and denoted D and special structures indicated by a stippled black box. The location of the seismic line can be seen in Figure 3-1 and the color-coding for the seismic reflectors can be seen in Figure 3-2.

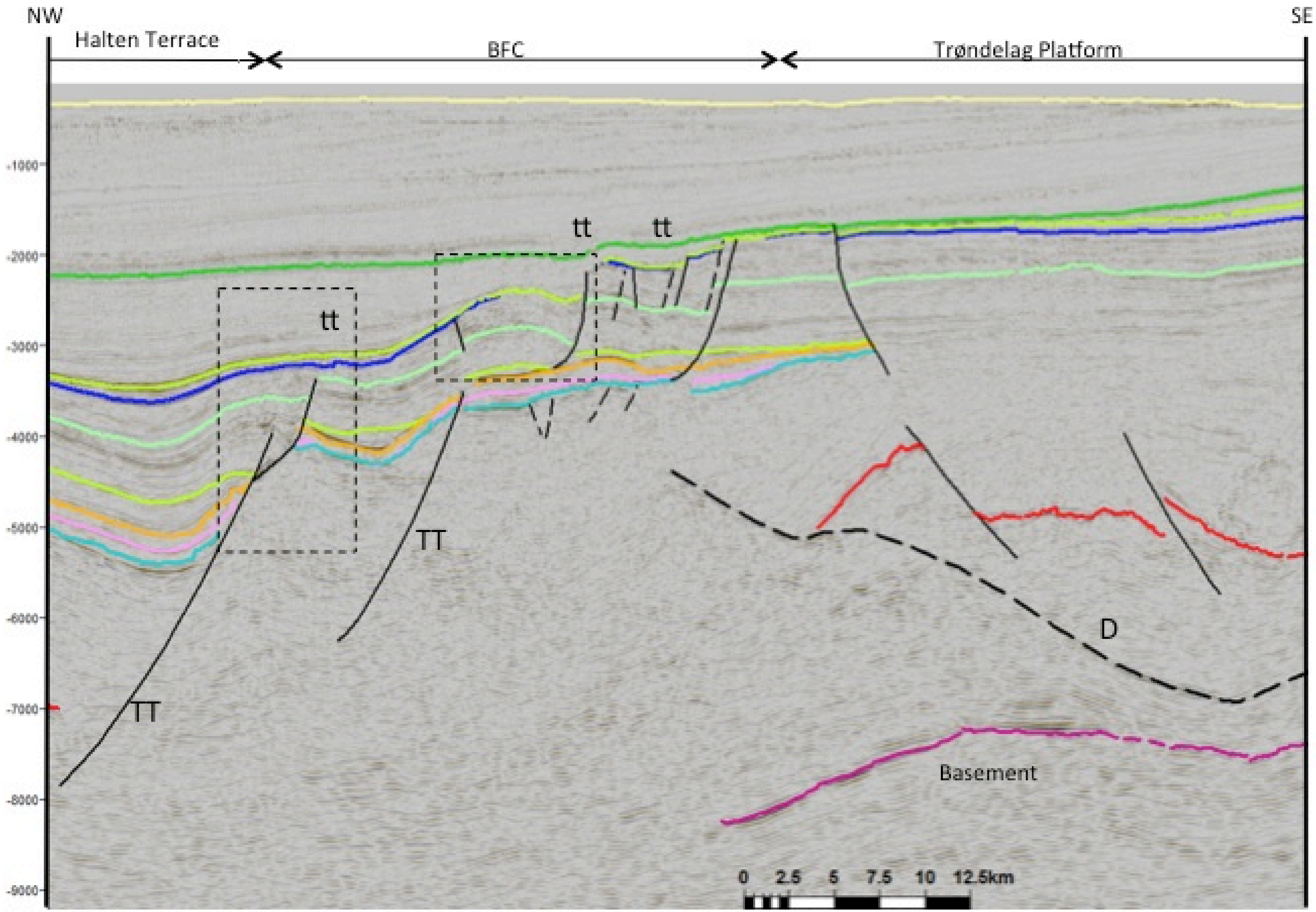


Figure 3-20b Interpretation of profile IX. Thick- and thin-skinned faults have been denoted TT and tt, detachments are stippled and denoted D and special structures indicated by a stippled black box. The location of the seismic line can be seen in Figure 3-1 and the color-coding for the seismic reflectors can be seen in Figure 3-2.

3.6.3 Fault geometry

The main structural styles observed in these profiles have been characterized as thick- or thin-skinned faults, because of the presence of (decoupling) Triassic evaporite layers. The thick-skinned and thin-skinned faults have been denoted TT and tt respectively (Figure 3-19 & 3-20). Further differentiation of the individual structures, is based on the variations in geometry (normal, listric, reverse), dip, and strike. The basement-related structures, in association with the Permian (and basement) reflection are not characterized as thick- or thin-skinned, since they do not interact with the Triassic evaporite unit.

Thick-skinned faults (TT)

Thick-skinned (coupled) faults are the faults that penetrate the whole sedimentary sequence (Chapter 3.4). Several normal, listric and blind thick-skinned faults are found in profiles VIII and IX (Figure 3-19 & 3-20). The faults bound distinct structural features, dislodge the evaporite layers, and impose displacement and rotation on the surrounding sedimentary strata. Most of the faults are normal faults, with listric characteristics at depth. In profiles VIII and IX the majority of the thick-skinned faults are located on the Halten Terrace, close to the Bremstein Fault Complex. However, two major thick-skinned faults are also observed on the SE side of the Trøndelag Platform, corresponding with the location of the Froan Basin. On the Halten Terrace the faults follow the dominant NE-SW orientation, and on the Bremstein Fault Complex the faults have N-S orientation and finally on the Trøndelag Platform the faults have a NE-SW orientation.

Thin-skinned faults (tt)

Thin-skinned (decoupled/partially coupled) faults are the faults that terminate in the evaporite layers. Several thin-skinned faults were interpreted in profiles VIII and IX (Figure 3-19 & 3-20). The thin-skinned structures are isolated structures, with an oblique orientation to the dominant strike (NE-SW & N-S). The faults appear primarily to be accommodation (or secondary) structures, evident by the occurrence of thin-skinned faults pre-dominantly in association with a thick-skinned fault, where they accommodate for extensional or compressional stresses.

A few sub-evaporite faults were also traced in profile VIII and IX. However, only the faults with sufficient displacement were traced. The majority of the sub-evaporite faults are located on the Halten Terrace and below the Bremstein Fault Complex, where they possess a NE-SW to N-S oriented strike and terminate upwards into the lower evaporite layer.

3.6.4 Fault distribution

The earliest faults observed in the study area seem to be of Permian age. The faults only penetrate the Late Paleozoic strata, including the interpreted top of the Permian reflection. The faults are low-angle faults, with a NW orientation on the Halten Terrace and a SE orientation on the Trøndelag Platform. Between the Permian reflection and the base evaporite reflection, limited thickness variations in the strata can be observed, as well as reflection displacements. A few pre-dominantly planar faults were interpreted in this interval, with NE-SW to N-S orientation. The late-Middle Triassic evaporite layers are both close to horizontal, with only a little variation in thickness. Between the top evaporite reflection and the interpreted top of the Åre Formation reflection, the strata have close to constant thickness, with exception of the areas where horst and graben structures are observed. The top of the Åre Formation is not mapped throughout, but the layers seem to be of equal thickness. Above the evaporite layers a large variety of faults can be observed, both listric and normal faults, extending from the base of the Cretaceous reflection to the evaporite reflections (denoted tt, Figures 3-19 & 3-20). The dominant fault trend is NE-SW, but subordinate orientations are also observed. In this interval several of the reflections are displaced by faults, thickness variations can be seen across the fault, as well as a few syn-sedimentary wedges in the hanging-walls. Termination of the base Cretaceous reflection, Cretaceous onlap and syn-sedimentary wedges are also observed, specifically within the graben structures and in the Bremstein Fault Complex hanging-wall. The strata located between the base of the Cretaceous and the base of the Cenozoic is pre-dominantly horizontal, onlapping the Cretaceous reflection, with little or no faulting observed.

3.6.5 Structures

Fault-propagation folds/Breached folds

A fault-propagation fold is visible in both of the profiles crossing the study area (illustrated by a stippled box). The structure is observed along the hanging-wall of the Bremstein Fault Complex, accompanied by a few distinct secondary structures: drag folds, monocline and two synthetic faults. Several breached folds are also visible on the Halten Terrace, but not in the selected profiles. A breached fold has previously been shown in Chapter 3.5.4 (Figure 3-16).

Fault-bend-fold

In Figure 3-19a (stippled box), a possible fault-bend-fold is illustrated. The structure is bounded by normal faults on each side and the interior strata dips towards the faults. Larger displacement is observed along the eastern side, compared to the western side. This is indicating that the eastern fault is the dominant fault and the western is a secondary (accommodation) fault. This observation is in accordance with the definition of a fault-bend fold, provided by Withjack et al. (2002).

Rollover anticline

A rollover anticline is observed in the middle of the Bremstein Fault Complex, indicated by a stippled box (Figure 3-20b). The structure has previously been discussed in Chapter 3.5.3 and illustrated in Figure 3-12.

Relay-ramp

The relay-ramp structure located in Profile IX, have previously been discussed in association with Profile IV (Chapter 3.5.4, Figure 3-15). However, there is a distinct difference between the relay-ramp in Profile IX (Figure 20b) compared with the relay-ramp in Profile IX (Figure 3-20a, stippled box). The structure is much wider and the layers within the structure are more horizontal. The structure is located in the Bremstein Fault Complex hanging-wall, on the eastern side of the fault-propagation-fold.

Grabens

Two graben structures are observed in profiles VIII and IX (Figures 3-19 & 3-20). The first one is located in the Bremstein Fault Complex and was discussed previously in Chapter 3.5.4 (Figure 3-14). The second one is located on the Halten Terrace. The structure corresponds with the Grinda Graben, previously described by Blystad et al. (1995) and Richardson et al. (2005). A stippled box indicates the location of the structures.

3.6.6 Basement-involved faulting and detachments (D)

Along the southern boundary between the Halten Terrace and the Trøndelag Platform (Froan Basin), several rotated half-grabens, basement-involved faults and a possible basement reflection is visible (Figures 3-19b & 3-20b). The seismic lines that cross this area are illustrated in Figure 3-21. Two new profiles extending from the Halten Terrace to the Froan Basin are introduced in this analysis, profiles A and B.

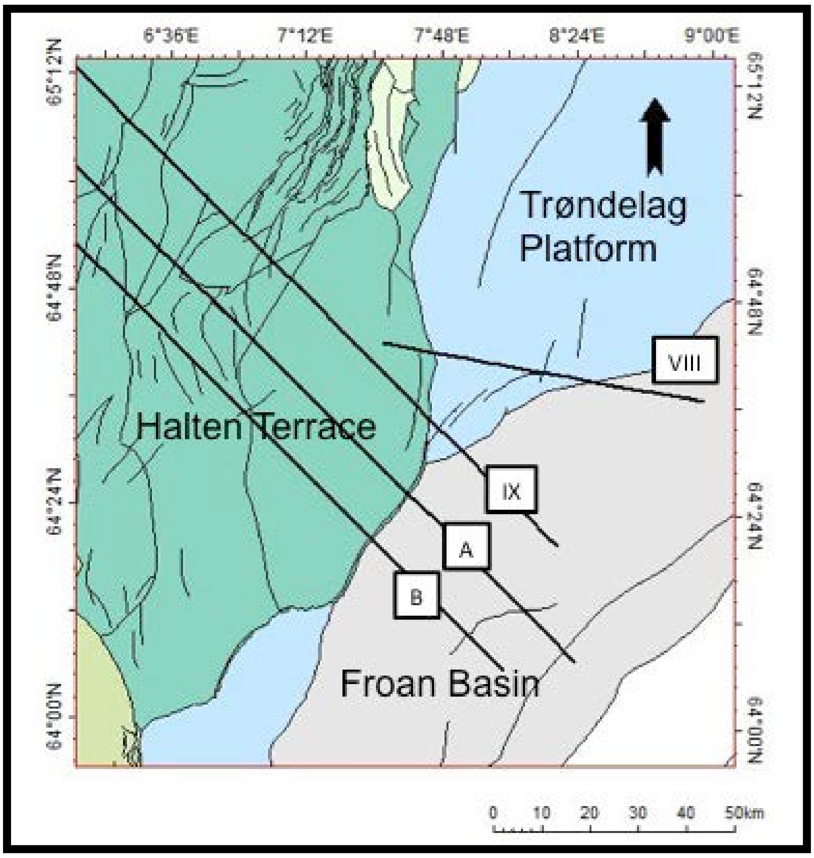
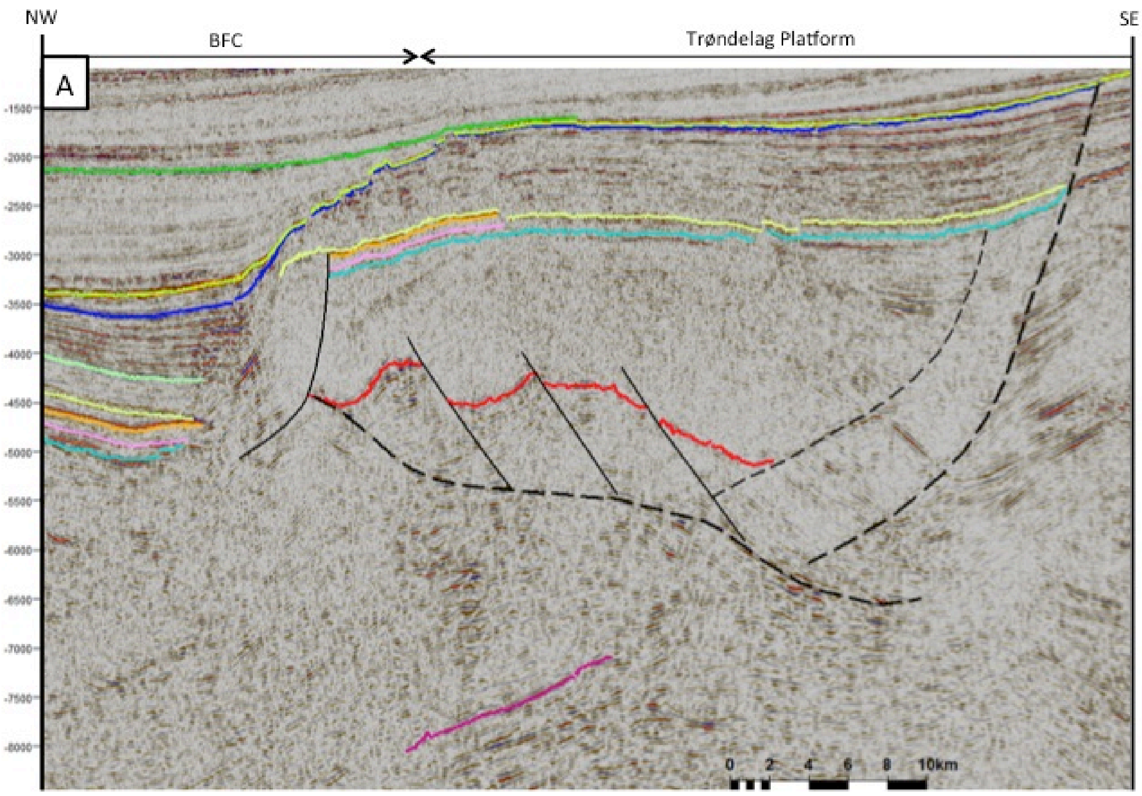


Figure 3-21 The seismic 2D line that illustrate basement, basement-involved faulting and a possible detachment. The location of the lines in relations to the other seismic lines used in this study is shown in Figure 3-1.

The basement reflection is observed below the Trøndelag Platform on the eastern side of the profiles. However, only a minor portion of the reflection was mapped and only in three of the profiles, due to the poor quality of the seismic data. The reflection was traced in Profile IX (Figure 3-20b), Profile A and Profile B (Figure 3-22). The reflection is located between 7-9 s TWT and visible as an undulating reflection dipping seawards.

The Froan basin located on the Trøndelag Platform is visible above the basement reflection, in three of the profiles. Within the basin rotated half-grabens are made visible by the interpreted Permian reflection (Chapter 3.2), between 4.5-7 s TWT. The half grabens are rotated landwards, bounded by low-angle normal faults, all of which terminate and merge against a low-angle reflection band, right above the basement reflection. This is an indication of the presence of a detachment zone. The general Paleozoic fault orientation is NE-SW. A few thick-skinned faults can also be seen extending into Mesozoic strata and crossing the evaporite layer.

Profiles VIII and B stand out in this analysis. In Profile VIII, only the Late Paleozoic graben structures and the detachment zone is visible. In Profile B only the basement reflection and the detachment zone is visible.



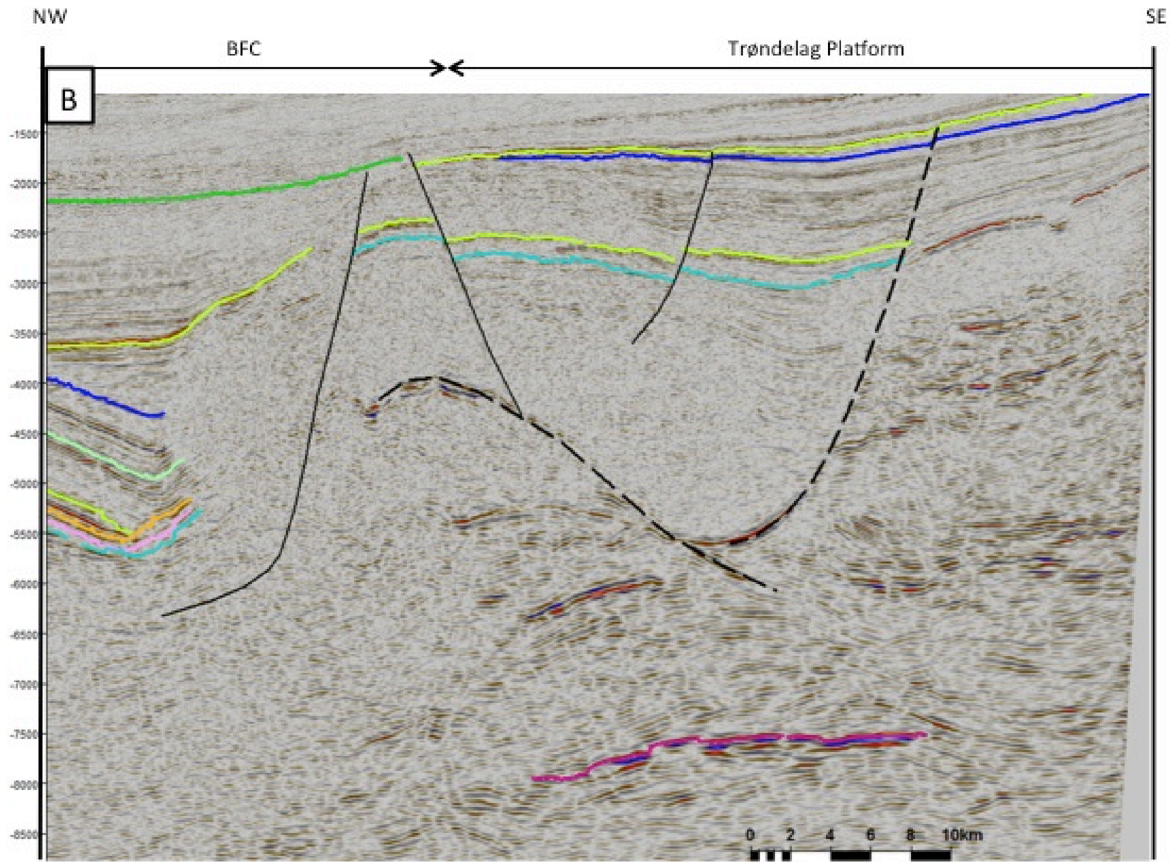


Figure 3-22 Two seismic profiles (A and B), illustrating the pre-middle Triassic geometry, between Halten Terrace and the Trøndelag Platform (Froan Basin). The location of the profiles is shown in Figure 3-21.

Chapter Four: Discussion

Chapter Four: Discussion

The purpose of this study, as introduced in chapter one, is to understand the mechanisms responsible for the structural geometry observed on the mid-Norwegian Continental Margin, specifically the Bremstein Fault Complex. This is to be accomplished by interpreting seismic data, with input from publications and analogue models (not performed by the author). In the section below, the results and observations from this interpretation will be discussed, emphasizing on (1) halokinesis and detachments, and (2) the role of inherited structures and reactivation, as well as (3) the regional stress regimes and tectonic history.

Several studies and publications have been done on the structural geometry of the Bremstein Fault Complex and the surrounding areas (Gabrielsen & Robinson, 1984; Withjack et al., 1989; Pascoe et al., 1999; Corfield & Sharp, 2000; Withjack & Callaway, 2000; Osmundsen et al., 2002; Withjack et al., 2002; Dooley et al., 2003; Richardson et al., 2005; Osmundsen & Ebbing, 2008; Marsh et al., 2010; Elliott et al., 2012; Wilson et al., 2013; Bell et al., 2014). These will be consulted in this discussion, in regards to augmentation and results.

4.1 Halokinesis and detachments

Evaporite sequences are deposited in four main settings, among them rifts and passive margins (Hudec & Jackson, 2007). Throughout the years, a number of studies have analyzed the influence of such an evaporite sequence on the Halten Terrace. This has specifically been done on the extensional fault systems: the Smørbukk and Trestakk fault systems (Marsh et al., 2010), the Nordland Ridge/Revfallet Fault Complex (Withjack et al., 1989; Pascoe et al., 1999; Dooley et al., 2003; Richardson et al., 2005) and the southern Bremstein Fault Complex/Vingleia Fault Complex (Wilson et al., 2013; Bell et al., 2014). Consequently, an evaporite-detachment in the Bremstein Fault Complex would be expected. A few recent publications have also discussed salt tectonics on the Bremstein Fault Complex (Withjack & Callaway, 2000; Withjack et al., 2002; Elliott et al., 2012; Wilson et al., 2013).

Detachment zones (e.g. evaporite deposits) possess the abilities to assert control over the structural setting by allowing the cover to slide relative to the basement. In areas where the units are thick enough, they may decouple the sub-evaporite strata from the supra-evaporite strata, fully or partially (Pascoe et al., 1999; Richardson et al., 2005; Wilson et al., 2013). The discussion will therefore include a comparison of the supra- and sub-evaporite fault systems, fault types, fault abundance, displacement, dip and strike, as well as associating structures. This will make it possible to evaluate the degree of separation and the difference in deformation between sub- and supra-evaporite layers. Furthermore, by comparing the seismic interpretations to experimental models, the presence of a detachment can be confirmed (or not) and the formation mechanisms responsible understood.

4.1.1 The Bremstein Fault Complex

Detachment layer

To determine the presence of a detachment layer the primary indicator is the occurrence of a rheological weak layer. In the Bremstein Fault Complex the potential detachment layer coincides with two closely spaced evaporite units deposited in the early-Late Triassic (Jacobsen & van Veen, 1984; Blystad et al., 1995). Scaled experiments have suggested that under low geological extension rates salt may decouple the brittle overburden from the faulted basement (Vendeville et al., 1995).

Fault and fold distribution

The second indication of a detachment is the presence of separate fault populations. In all of the profiles analyzed in this study, separate fault populations were evident. The sub-evaporite faults are widely distributed planar faults, with small displacement, terminating upwards into the evaporite layers, with NE-SW to N-S orientation. The supra-evaporite faults are either listric or normal faults, extending from the BCU to the evaporite layers, with a NE-SW orientation. The supra-evaporite faults have variable displacement and are laterally associated with thick-skinned faults. By comparing the observed results with the quantitative fault study performed by Wilson et al. (2013) on the Halten Terrace fault systems, an even clearer difference between the supra-and sub-evaporite faults is evident.

Another observation is the difference in fault abundance. The fault population above the detachment is far greater than the population below. This illustrates that the faults present above and below the detachment, are of different populations, initiating and terminating independently from each other. These results also correlate with the publication by Wilson et al. (2013) and further promotes the hypotheses of a decoupled system, consisting of different stress settings across the detachment.

Furthermore, presence of through-going thick-skinned faults promotes the hypotheses that the system is not completely decoupled, but rather partially-decoupled. Partially-decoupled systems are comparable to the firm-linked systems, defined by Harvey and Stewart (1998).

Partially-decoupled or firm-linked systems

The Bremstein Fault Complex is characterized by thick-skinned faults formed by the direct or indirect linkage of thin-skinned faults during extension. This coincides with published characterizations of faults within rift basins (Withjack et al., 1989; Vendeville et al., 1995; Harvey & Stewart, 1998; Withjack et al., 2002; Wilson et al., 2013). The linkage then results in the formation of specific structures, like the ramp-flat-ramp (linkage of two thin-skinned faults) and the fault-propagation-fold (propagation of a thick-skinned fault) observed in profiles I, V, VIII and IX (Figures 3-11, 3-14, 3-16, 3-19, & 3-20). The formation of such structures lead to the destabilization of the system and the formation of accommodation structures (grabens, rollover anticlines, antithetic and synthetic faults). In a publication by Withjack et al. (1989), a schematic cross section is presented with different accommodation structures formed by normal detachment faults and blind faults, in the presence of a detachment. It is therefore reasonable to assume that the formation mechanism for thick-skinned faults is linkage due to regional extension, whilst the formation mechanism for thin-skinned structures, is both regional extension and system destabilization. This hypothesis is in accordance with Wilson et al. (2013)´s postulation that in vertically decoupled fault systems, supra-evaporite faults form in response to regional extension and gravity-driven processes. The hypothesis is also in accordance with experimental models performed by Vendeville et al. (1995). This is then indicating the formation mechanisms behind the Bremstein Fault Complex.

An exception to this reasoning is Segment 3. In Segment 3 only one thick-skinned fault is visible and the segment consists of a simple geometry with generally only supra-evaporite, thin-skinned normal faults and horizontal layering. This indicates that Segment 3 has been subjected to a different formation mechanism than the rest of the Bremstein Fault Complex. A vague conclusion can therefore be proposed; the northern segment of the Bremstein Fault Complex is most likely not controlled by halokinesis or at least not to the extent observed in segments 1 and 2.

4.1.2 Bremstein Fault Complex analogue models

Analogue models are often used to reconstruct specific structural geometries. They are interpretation tools that can help shedding light on possible formation mechanisms. The analogue model preferred in this situation has one detachment zone representing the evaporite layer and two deformation phases representing deformation pre- and post-evaporite deposition. Three models have been selected to illustrate the similarities between the geometries observed on the Halten Terrace and experimental models. Two of the models, provided by Zalmstra (2013) & Braut (2012) and Vendeville et al. (1995), will be compared to profiles I (Segment 1) and V (Segment 2). The third model is by Withjack and Callaway (2000) and Withjack et al. (2002), and in the publication the model is compared to profile VIII (Segment 2). No model will be compared to the profiles in Segment 3.

Models for Profiles I and V

When the key profiles from the Bremstein Fault Complex are compared to the analogue models there is a clear resemblance in the structural geometry (Figure 4-1). In analogue Model A, three grabens and several faults have formed above and terminated at the detachment layer. Below, the strata is dominantly horizontal with no visible structural elements, except for the one major blind normal fault (MF5). This is also evident in profiles V and I. Both profiles have graben formation, faults terminating in the weak layer and a major blind normal fault (MF5). Analogue Model B is a much simpler model, consisting of fewer listric faults and graben structures. However the model is similar to the structural geometry in profiles V and I. The graben structure, the blind normal fault and the pre-dominantly horizontal strata below the weak layer, present in Model B is also present in profiles V and I. Deformation of the detachment zone, in the form of accumulation and withdrawal structures, can also be correlated between the profiles and the models. This is because the accumulation and withdrawal structures are comparable to actual salt swells and salt welds.

Faults MF1, MF3, MF5, NF1 and MF4 in Model A, correlate with faults presented with the same notation in profile I (Figure 4-1). Model A and Profile I also have a similar graben structure, located between MF3 and MF4. In Model B, the faults only correlate with faults MF3, MF4 and MF5 from Profile I. Also the same graben structure between MF3 and MF4, correlate with the graben structure located in Model B. This indicates that Model A has the best fit with the actual structural geometry present in Profile I and thus Segment 1, while Model B is only similar. However there are some distinct differences between model A and Profile I, among them the presence of a second graben in the model, as well as the presence of a large rotated fault block in the hanging-wall. The same could be said about Profile I, there are more thin-skinned structures in the Bremstein Fault Complex, then presented in the experimental model.

In the comparison between Models A and B with Profile V, it is Model B that is most similar due to its simple geometry. In the correlation between Model A and Profile V, faults MF2, MF6 and MF5 in Model A correlate with faults MF1, MF2 and MF5 in profile V. Three of the master faults present in Profile V (MF2, MF6 and MF5) correlate with the three master faults located in Model B. This indicates that Model B has the best fit with the actual structural geometry present in Profile V and thus Segment 2.

The observations made in this comparison between the experimental models and the seismic profiles, are in accordance with the publication by Withjack et al. (1989) and Wilson et al. (2013). In the publications the main mechanism behind the geometry observed in the experimental models, is believed to be the thick-skinned blind master fault, while the other structures observed are only accommodation structures formed in response to the fault activity along the blind fault. The blind fault in both profiles and both models is similar, while the thin-skinned faults in both the profiles and both models are different.

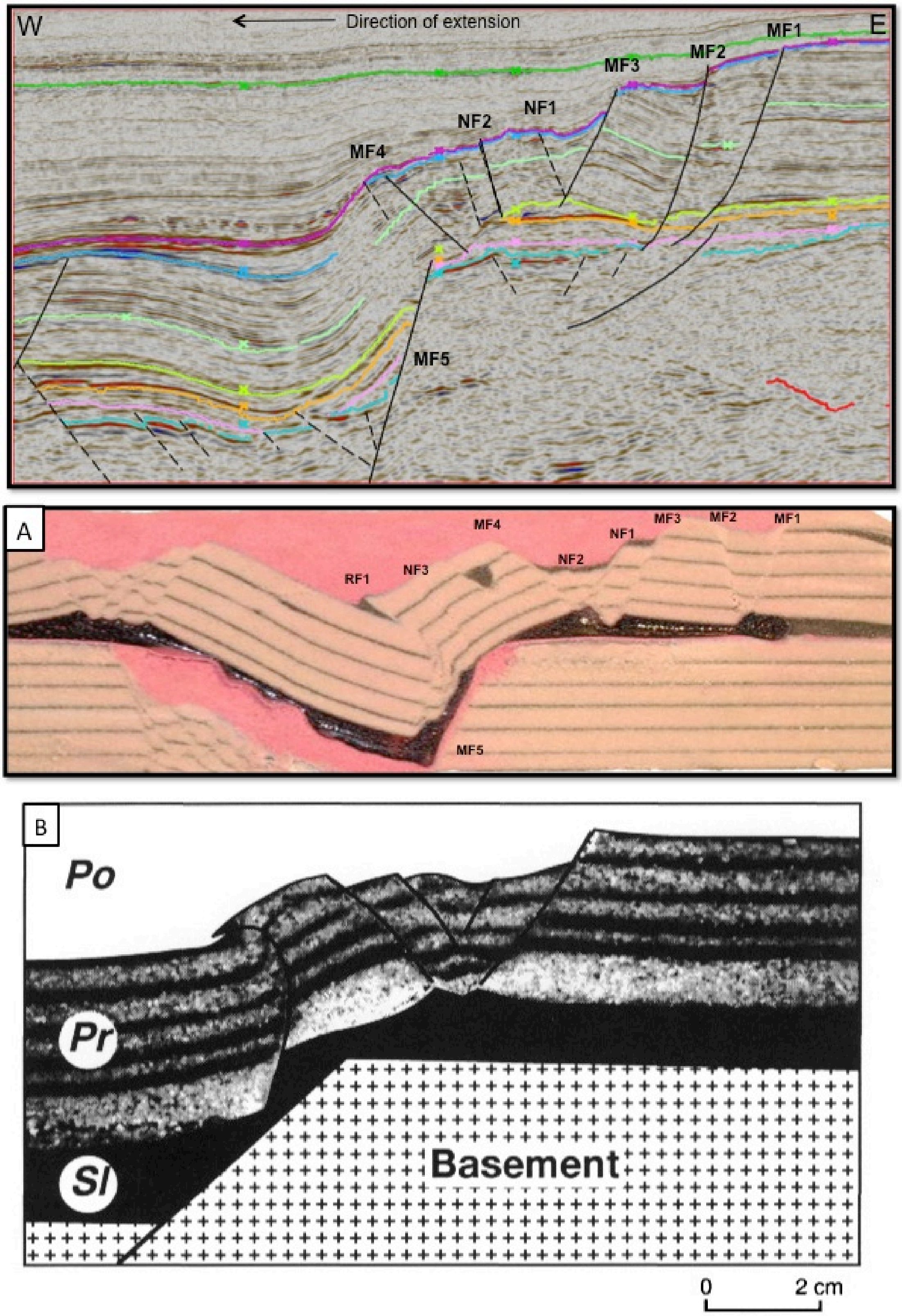


Figure 4-1 The Triassic evaporite detachment illustrated in Profile I (Figure 3-11) compared with an analogue model by (A) Zalmstra (2013) & Braut (2012) and (B) Vendeville et al. (1995)

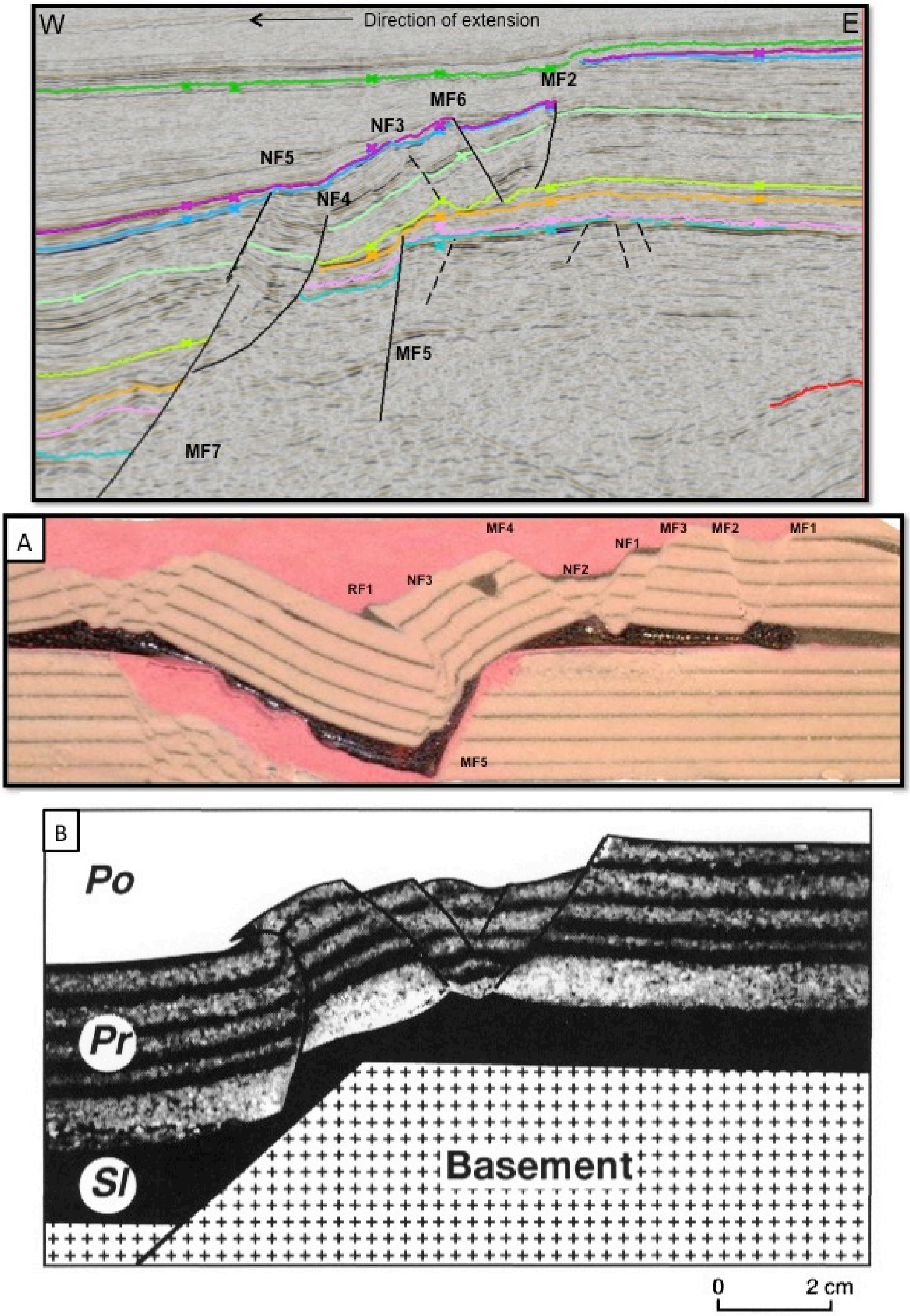


Figure 4-2 The Triassic evaporite detachment illustrated in Profile V (Figure 3-16) compared with an analogue model by (A) Zalmstra (2013) & Braut (2012) and (B) Vendeville et al. (1995)

Model for Profile VIII

In two publications by Withjack and Callaway (2000) and Withjack et al. (2002), experimental models simulating extensional deformation were compared to real life examples. The Bremstein Fault Complex is one of the structures used in their study. Conveniently the seismic line used in their comparison, is also used in this study. The seismic line that was used, is the one referred to as Profile VIII, illustrated in Figure 3-19. A sketch of this seismic line is illustrated below (Figure 4-3).

The observations from Profile VIII are consistent with the physical model. In both the model and the profile a broad extensional forced fold is visible above a blind master fault, located in the hanging-wall of the Bremstein Fault Complex. The model and the profile also have widely distributed accommodation structures (a graben, antithetic and synthetic faults) in the supra-evaporite layer.

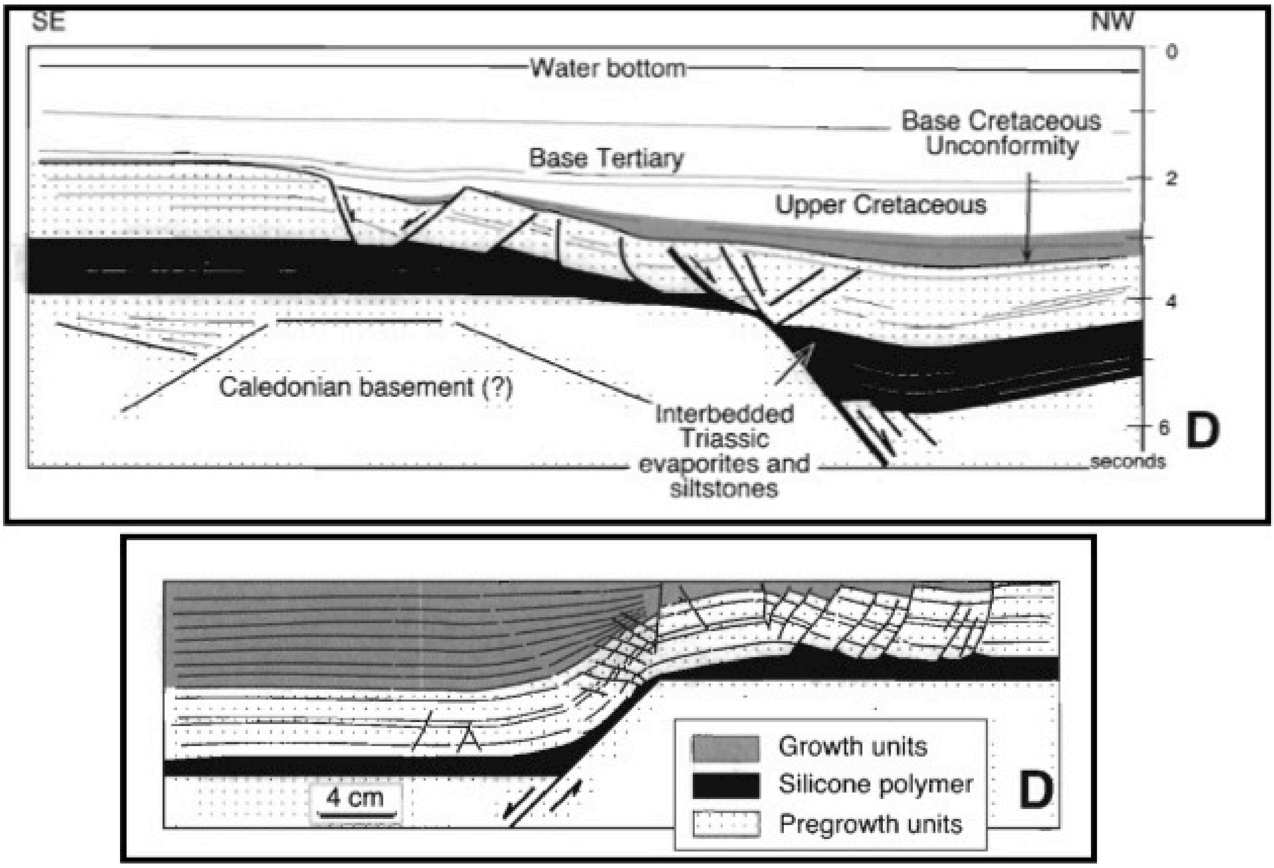


Figure 4-3 The Triassic evaporite detachment illustrated in a sketch of Profile VIII (Withjack et al., 2002) compared with an analogue model by Withjack and Callaway (2000) and Withjack et al. (2002).

4.2 Inherited structures and reactivation

In this section the possibility of inherited structures below the study area will be discussed. With the seismic interpretation performed in this study, published seismic data analysis (Bukovics et al., 1984; Blystad et al., 1995; Breivik et al., 2011) bore hole analysis (Bugge et al., 2002), gravity, magnetic and velocity data (Doré et al., 1997; Skilbrei & Olesen, 2005; Breivik et al., 2011) and offshore – onshore comparisons (Braathen et al., 2000; Braathen et al., 2002; Osmundsen et al., 2002) the presence of inherited structures can be confirmed (or denied). Until present, the seismic resolution at depth has put some constraint on the analysis of such structures.

Paleozoic strata

Due to the poor resolution of the seismic data and the presence of only shallow wells within the study area, the only reflection that was interpreted below the late-Middle Triassic, was a possible Top Permian reflection. A possible basement reflection was also interpreted, but only in a few of the profiles. However, in a publication by Breivik et al. (2011) a velocity model along a profile (Figure 4-4), close to Profile IX (Figure 3-20a) is presented. In this publication the presence of Devonian strata is confirmed, with the measurement of an intermediate velocity (5.4-5.8 km s-1) layer at about 6-7 km below the Halten Terrace. The publication interprets the velocity to be well-consolidated predominantly Devonian strata. The presence of a Paleozoic strata is further acknowledged in a publication by Bugge et al. (2002), where a bore hole analysis is performed and the crystalline basement is presumed to be located around 8-10 km below the Halten Terrace and the Trøndelag Platform.

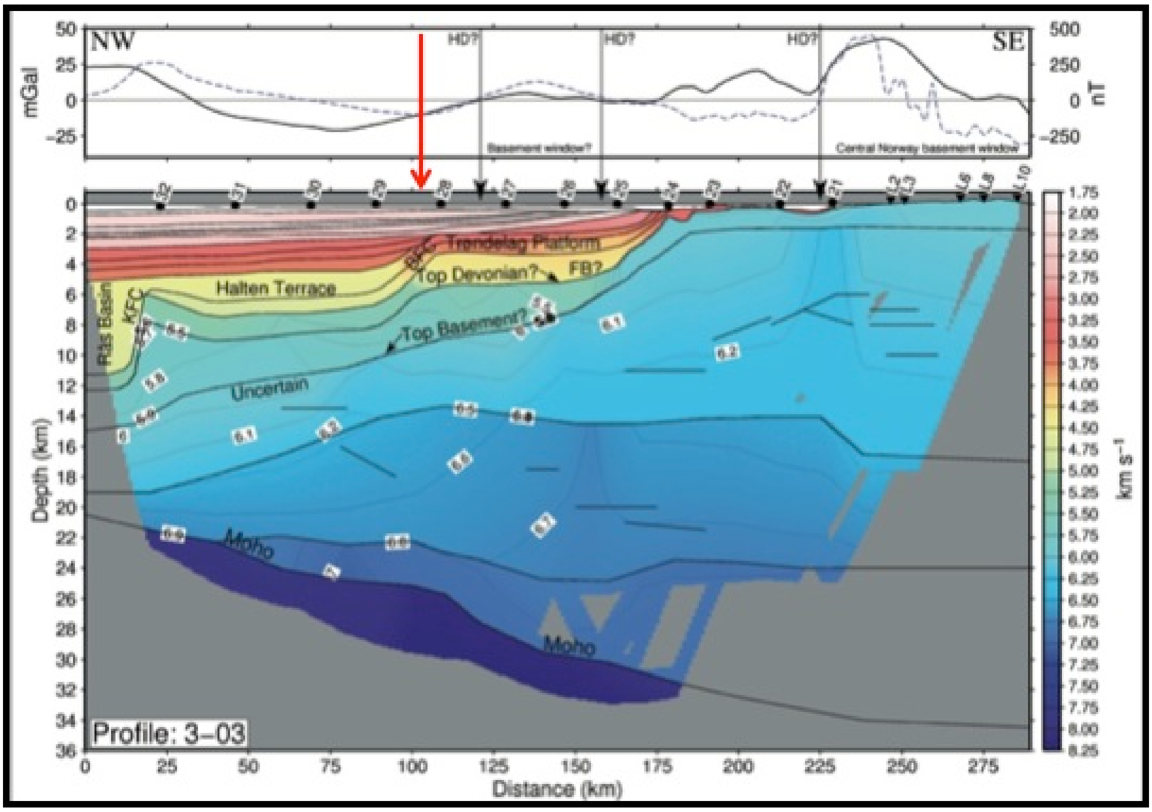


Figure 4-4 A crustal velocity model close to Profile VIII (Figure 3-19b), provided by Breivik et al. (2011). The red arrow indicates the location of the Bremstein Fault Complex.

Paleozoic architecture

Deep-seated Late Paleozoic half-grabens were interpreted below both the Halten Terrace and the Trøndelag Platform boundary, in the vicinity of the Froan Basin, between 4.5 -7 s TWT. On the Halten Terrace, the Permian reflection is terminated by faults that have rotated the Paleozoic sedimentary layers basinwards. Beneath the Trøndelag Platform, the Permian reflection highlights the presence of rotated half-grabens. The grabens are bounded by large magnitude low-angle normal faults with NE-SW orientation. The bounding faults merge and terminate in a low-angle reflection band, located right above a basement reflection. The basement reflection was only observed in three of the seismic profiles, where it was characterized as an undulating reflection band with seawards dip.

These interpretations are in accordance with Osmundsen et al. (2002) and Osmundsen and Ebbing (2008). The resemblance is especially clear when the geoseismic sections provided by Osmundsen et al. (2002) are compared to profiles VIII and B. Profile VIII (Figure 3-19b) resembles part of Figure 4-5A and Profile B (Figure 3-22) resembles part of Figure 4-5B. In the geoseismic sections pre-Middle Triassic half-grabens are interpreted, as well as a low-angle detachment and a basement reflection. Reactivated faults around the Jurassic-Cretaceous boundary and an antiformal culmination, interpreted by Osmundsen and Ebbing (2008) as a metamorphic complex, are also common traits. This culmination was also identified by Breivik et al. (2011). In the publication the culmination is characterized as a distinct, dome-shaped lower-crustal body and identified with a velocity around 6.6-7.0 km s^{-1}.

The overall structural trends are also in accordance with a description of the Permo-Triassic extension of the Foran Basin, made by Doré et al. (1997) and Doré et al. (1999). The publication describes Late Paleozoic architecture, consisting of half-grabens arranged in a left-stepping, en echelon pattern, resembling the interpreted architecture in this study.

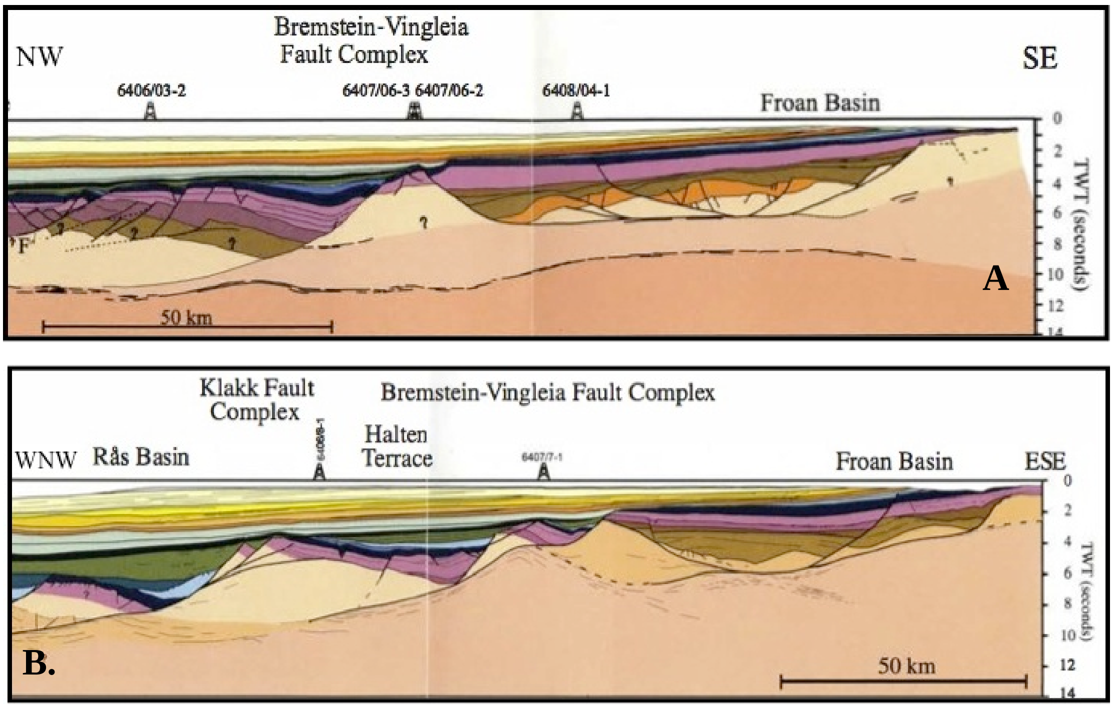


Figure 4-5 Two geoseismic sections transversing the Bremstein Fault Complex/Vingleia Fault Complex and the Froan Basin. Modified from Osmundsen et al. (2002).

Continuation of detachment systems

On the Mid Norwegian rift margin NE-SW, N-S and NW-SE fault trends dominate, these trends are comparable with fault patterns onshore Norway (Doré et al., 1997; Skogseid et al., 2000). This has lead to the hypothesis that reactivation of low-angle Devonian shear zones, like the Høybakken detachment or the Kollstraumen detachment, could be responsible for a reactivation in the Mesozoic–Cenozoic (Osmundsen et al., 2002; Skilbrei & Olesen, 2005; Breivik et al., 2011).

Several authors have voiced speculation regarding this hypothesis, among them Doré et al. (1997) and in a publication by Breivik et al. (2011) this hypostasis is challenged. In the publication a velocity profile (Figure 4-4) crosses the Høybakken detachment and the publication states that a detachment would be proven if the profile detects a sharp changes when crossing from amphibolite and granulite facies rocks. The velocity did not drastically change across the profile; this means that there is probably no continuation of the onshore detachments. The profile did however indicate a rapid fall in velocity below the Trøndelag Platform, indicating a detachment accommodating Devonian strata towards the northwest. This Devonian detachment can be correlated to the detachment observed in the four profiles crossing the Halten Terrace, Bremstein Fault Complex and Froan Basin/Trøndelag Platform, as well as the detachment proposed by Osmundsen et al. (2002).

4.3 Tectonic events

Following the compressional regime of the Caledonian orogeny, the Mid-Norwegian Continental Margin has been subjected to at least five major tectonic events (Bukovics et al., 1984; Price & Rattey, 1984; Blystad et al., 1995; Doré et al., 1999; Brekke, 2000; Skogseid et al., 2000; Færseth & Lien, 2002; Osmundsen et al., 2002; Faleide et al., 2008; Faleide et al., 2010). Evidence of these regional extensional events, in addition to a few local tectonic phases, can be visualized on the seismic profiles from the Halten Terrace and the Bremstein Fault Complex. The phases of extension are the: (1) Late Permian - Early Triassic, (2) Late Triassic – Early Jurassic, (3) late-Middle Jurassic to Early Cretaceous and (4) Late Cretaceous to Eocene (Figure 4-5).

The earliest rifting events on the Mid-Norwegian Continental Margin occurred in the Late Paleozoic-Early Mesozoic. The specific timing and extent of this event is uncertain, several events have therefore been proposed, like mid-Carboniferous, Carboniferous-Permian, and Permo-Triassic (Ziegler, 1988; Tsikalas et al., 2012). Evidence of this is however scarce on the Halten Terrace and Trøndelag Platform, due to poor resolution of the seismic data. The earliest tectonic activity visible is the Permo-Triassic extensional event (Blystad et al., 1995; Pascoe et al., 1999; Withjack & Callaway, 2000; Osmundsen et al., 2002; Osmundsen & Ebbing, 2008), visible in the form of a block-faulted terrain beneath the Halten Terrace and Froan Basin/Trøndelag Platform (not the Bremstein Fault Complex). In the seismic data (Figures 3-19 & -20) NE-SW and N-S oriented fault terminations of the Permian reflection, as well as rotated half-grabens, are visible between 4,5-8 s TWT (Chapter 3.6.3 & 3.6.6, Figures 3-19b, 3-20b, 3-22). The metamorphic core complex visible in Figure 3-22b, is also evidence of a Permo-Triassic rift event (Breivik et al., 2011). A period characterized by little or no faulting followed. This is evident by limited thickness variations in the strata, little reflection displacement and the deposition of two evaporite layers. The evaporite layers are semi-horizontal, with no major thickness variations (Figure 3-19a, Profile VIII). The next extensional event that affected the area was in the Late Triassic – Jurassic times (Gabrielsen et al., 1999; Brekke, 2000; Bugge et al., 2002; Osmundsen et al., 2002). Fault movement in the Late Triassic, Early Jurassic and Late Jurassic is evident by reflection displacements, reflection terminations and thickness variations across the faults (Figure 3-8, Profile I). The major rift event in the study area occurred between the Late Jurassic and the Early Cretaceous (Pascoe et al., 1999; Withjack & Callaway, 2000; Richardson et al., 2005; Bell et al., 2014). The formation of the Halten Terrace as an independent structure was initiated in this event (Blystad et al., 1995). There was a regional E-W least principal stress direction at this time, evident by the N-S strike of the Bremstein Fault Complex. Evidence of the rift event is especially distinct along the base Cretaceous reflection, by reflection displacements and reflection terminations (Figures 3-12 & 3-14). By the Early Cretaceous rift activity on the Bremstein Fault Complex and the Halten Terrace ceased, evident by Cretaceous syn-sedimentary wedges and Cretaceous onlap on the Bremstein Fault Complex hanging-wall. Even though rift activity ceased in the study area at this time, there has been great debate on how far into the Early Cretaceous extension continued on the Mid-Norwegian margin. Most authors have deemed basin formation and lateral thickness variations, wedge-shaped sedimentary bodies, influx of coarse clastics, onlap surfaces and base Cretaceous reflection terminations to Mid-Cretaceous rifting (Færseth & Lien, 2002; Tsikalas et al., 2012). The last few years evidence for an Aptian-Albian rifting event in the NE Atlantic margin has increased and rifting has been documented in several places along the margin (Tsikalas et al., 2012). However, one author has argued for a period of quiescence in the Cretaceous, separating the main rift episode into Middle/Late Jurassic and earliest Cretaceous events (Færseth & Lien, 2002). The author proposes that features said to be indicative of Cretaceous tectonic phases can be explained by differential subsidence and other mechanisms, with out invoking tectonism.

A later phase of rifting leading to reactivation, occurred in the Middle to Late Cretaceous. This phase resulted in the down-faulting and consequently the final stages of Bremstein Fault Complex formation. Activity along the major faults located in the Bremstein Fault Complex illustrates this. Local reactivations, pre-dominantly horizontal layering, onlap on the base Cretaceous and little or no faulting on the Halten Terrace and Trøndelag Platform characterize the Late Cretaceous to Eocene extensional event. This is indicating that following the Early Cretaceous most of the rifting ceased and the deposition of the Cretaceous strata was passive.

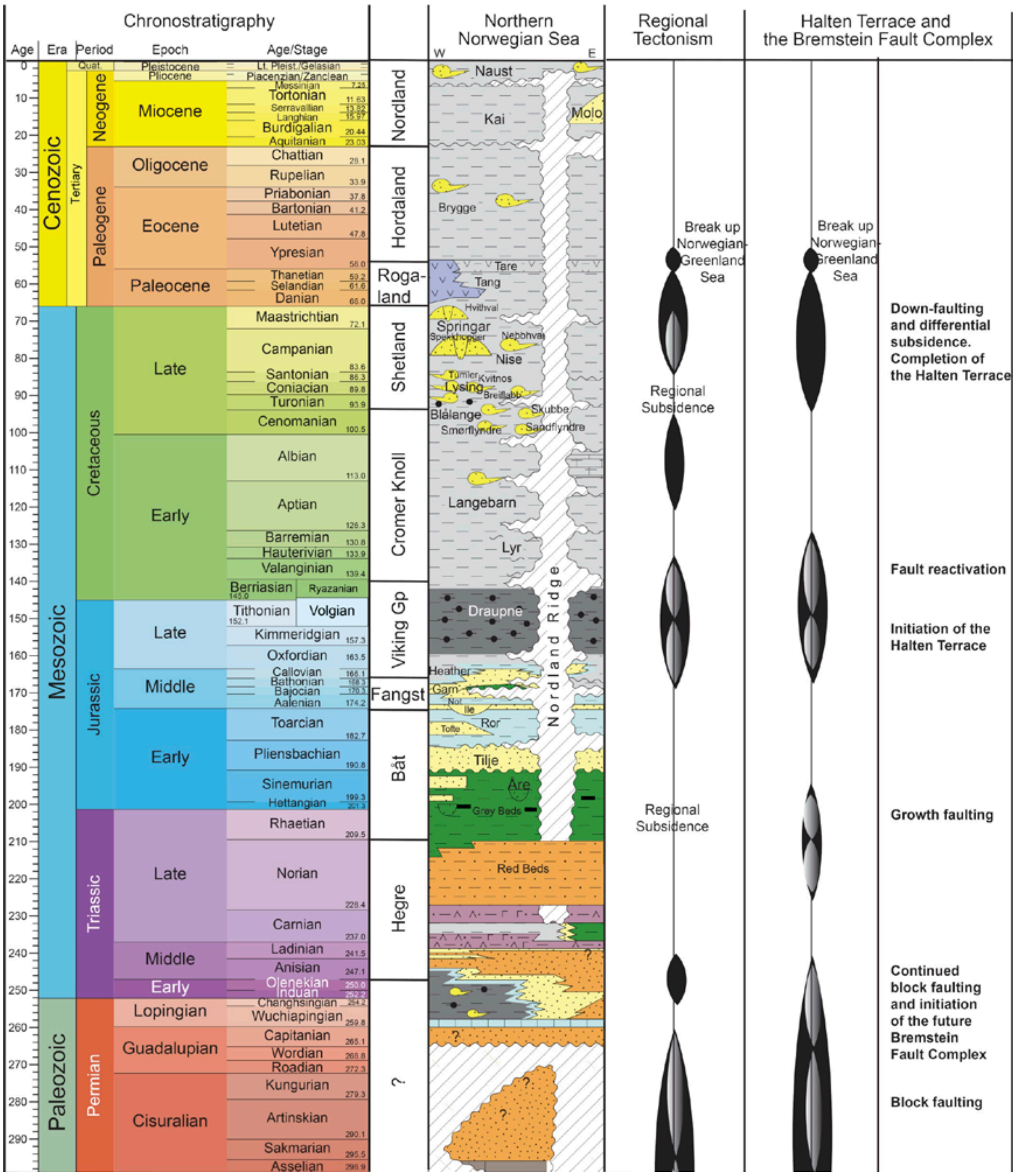


Figure 4-5 A schematic diagram of the lithostratigraphy on the Mid-Norwegian Continental margin and the main tectonic events. Modified after Gradstein et al. (2010).

Chapter Five: Conclusion

After the interpretation and analysis of the Bremstein Fault Complex, with special emphasis on the structural geometries, timing of faulting, reactivation, salt tectonics and the possibility of inherited Late Paleozoic structuring. A conclusions have been reached.

The structural setting observed in the Bremstein Fault Complex, can be divided into two levels, namely the post-evaporite Late Triassic and younger strata, and the pre-evaporite Late Paleozoic-Early Mesozoic strata. The study can conclude that the evaporite layers function as a detachment:

- The presence of a detachment is in accordance with the seismic analysis, analogue models and previous publications.
- The experimental models give a good representation of the structural setting in the Bremstein Fault Complex, even when the models are made separately.
- Salt is a controlling factor in the structuring of the Bremstein Fault Complex.
- The northern part of the complex indicates less salt control.
- The fault complex shows indications of fault segmentation, although definite signs of this have not been obtained with the data at hand.

The Bremstein Fault Complex is likely to have been developed due to pre-existing zones of weakness inherited from earlier tectonic movement, in the Devonian and the Permo-Triassic, related to a Caledonian structural grain:

- The study revealed the presence of a detachment of possible Devonian age.
- The study revealed the presence of a Permo-Triassic fault array.
- Thick-skinned faults extending across the Jurassic-Cretaceous boundary reveal reactivation.

The Bremstein Fault Complex has been tectonically active in four distinct phases: (1) Permo-Triassic, (2) Late Triassic-Earl Jurassic, (3) late-Middle Jurassic-Early Cretaceous, and (4) Late Cretaceous-Eocene.

Allaby, Michael. (2008). *Dictionary of Earth Sciences* (Third ed.): Oxford University Press.

Bell, R. E., Jackson, C., Elliott, G. M., Gawthorpe, R. L., Sharp, Ian R., & Michelsen, Lisa. (2014). Insights into the development of major rift‐ related unconformities from geologically constrained subsidence modelling: Halten Terrace, offshore mid Norway. *Basin Research, 26*(1), 203-224.

Blystad, P., Brekke, H., Færseth, R. B., Larsen, B. T., Skogseid, J., & Tørudbakken, B. (1995). *Structural elements of the Norwegian Continental Shelf. Part 2: The Norwegian Sea region* (Vol. No. 8): The Norwegian Petroleum Directorate.

Braathen, Alvar, Nordgulen, Øystein, Osmundsen, Per-Terje, Andersen, Torgeir B., Solli, Arne, & Roberts, David. (2000). Devonian, orogen-parallel, opposed extension in the Central Norwegian Caledonides. *Geology, 28*(7), 615-618.

Braathen, Alvar, Osmundsen, Per Terje, Nordgulen, O., Roberts, David, & Meyer, Gurli B. (2002). Orogen-parallel extension of the Caledonides in northern Central Norway: an overview. *Norsk Geologisk Tidsskrift, 82*(4), 225-242.

Braut, Hanna. L. (2012). *Analogue Modelling of Detachment Zones and Structural Analysis of the Ringvassøy-Loppa Fault Complex, SW Barents Sea.* UIO.

Breivik, Asbjørn Johan, Mjelde, Rolf, Raum, Thomas, Faleide, Jan Inge, Murai, Yoshio, & Flueh, Ernst R. (2011). Crustal structure beneath the Trøndelag Platform and adjacent areas of the Mid-Norwegian margin, as derived from wide-angle seismic and potential field data. *Norwegian Journal of Geology, 90*, 141-161.

Brekke, H. (2000). The tectonic evolution of the Norwegian Sea continental margin, with emphasis on the Vøring and Møre basins, in Dynamics of the Norwegian Margin. *Geological Society, London, Special Publications, 167,* 327-378.

Brekke, H., & Riis, F. . (1987). Tectonics and basin evolution of the Norwegian shelf between 62N and 72N. *Norsk Geologisk Tidsskrift, 67*, 295-322.

Bugge, T., Ringas, J. E., Leith, D. A., Mangerud, G., Weiss, H. M., & Leith, T. L. (2002). Upper Permian as a new play model on the mid-Norwegian continental shelf: Investigated by shallow stratigraphic drilling. *AAPG bulletin, 86*(1), 107-127.

Bukovics, C., Cartier, E. G., Shaw, N. D., & Ziegler, P. A. (1984). Structure and development of the mid-Norway continental margin *Petroleum Geology of the North European Margin* (pp. 407-423): Springer.

Bøen, F., Eggen, Svein, & Vollset, Jan. (1984). Structures and basins of the margin from 62 to 69 N and their development. *Petroleum Geology of the North European Margin*.

Corfield, S., & Sharp, I. R. (2000). Structural style and stratigraphic architecture of fault propagation folding in extensional settings: a seismic example from the Smørbukk area, Halten Terrace, Mid‐ Norway. *Basin Research, 12,* 329-341.

Dalland, A., Worsley, D., & Ofstad, K. (1988). *A Lithostratigraphic Scheme for the Mesozoic and Cenozoic and Succession Offshore Mid-and Northern Norway* (Vol. No. 4): The Norwegian Petroleum Directorate.

Dooley, T., McClay, K. R., & Pascoe, R. (2003). 3D analogue models of variable displacement extensional faults: applications to the Revfallet Fault system, offshore mid-Norway. *Geological Society, London, Special Publications, 212*(1), 151-167.

Doré, A. G., Lundin, E. R., Fichler, C., & Olesen, O. (1997). Patterns of basement structure and reactivation along the NE Atlantic margin. *Journal of the Geological Society, 154*(1), 85-92.

Doré, A. G., Lundin, E. R., Jensen, L. N., Birkeland, Ø, Eliassen, P. E., & Fichler, C. (1999). *Principal tectonic events in the evolution of the northwest European Atlantic margin.* Paper presented at the Geological Society, London, Petroleum Geology Conference series.

Elliott, Gavin M., Wilson, Paul, Jackson, Christopher A‐L, Gawthorpe, Robert L., Michelsen, Lisa, & Sharp, Ian R. (2012). The linkage between fault throw and footwall scarp erosion patterns: an example from the Bremstein Fault Complex, offshore Mid‐Norway. *Basin Research, 24*(2), 180-197.

Faleide, J. I., Bjørlykke, K., & Gabrielsen, R. H. (2010). Geology of the Norwegian Continental Shelf *Petroleum Geoscience from sedimentary environments to rock physics* (pp. 467-499): Springer.

Faleide, J. I., Tsikalas, F., Breivik, A. J., Mjelde, R., Ritzmann, O., Engen, Ø., . . . Eldholm, O. (2008). Structure and evolution of the continental margin off Norway and the Barents Sea. *Episodes, 31*, 82 -91.

Færseth, R. B., & Lien, T. (2002). Cretaceous evolution in the Norwegian Sea—A period characterized by tectonic quiescence. *Marine and Petroleum Geology, 19*, 1005-1027.

Gabrielsen, R. H., Odinsen, T., & Grunnaleite, I. (1999). Structuring of the Northern Viking Graben and the Møre Basin; the influence of basement structural grain, and the particular role of the Møre-Trøndelag Fault Complex. *Marine and Petroleum Geology, 16*(5), 443-465.

Gabrielsen, Roy H., Færseth, Roald, Hamar, Georg, & Rønnevik, Hans. (1984). Nomenclature of the main structural features on the Norwegian Continental Shelf north of the 62nd parallel *Petroleum Geology of the North European Margin* (pp. 41-60): Springer.

Gabrielsen, Roy H., & Robinson, Charlotte. (1984). Tectonic inhomogeneities of the Kristiansund—Bodø Fault Complex, offshore mid-Norway *Petroleum Geology of the North European Margin* (pp. 397-406): Springer.

Gradstein, F.M, Anthonissen, E., Brunstad, H., Charnock, M., Hammer, O., Hellem, T., & Lervik, K.S. (2010). Norwegian Offshore Stratigraphic Lexicon (NORLEX). *Newsletters on Stratigraphy, 44*, 73-86.

Harvey, Michael J., & Stewart, Simon A. (1998). Influence of salt on the structural evolution of the Channel Basin. *Geological Society, London, Special Publications, 133*(1), 241-266.

Herron, Donald A. (2011). *First Steps in Seismic Interpretation*. Society of Exploration Geophysicists: Rebecca B. Latimer.

Heum, O. R., Dalland, A., & Meisingset, K. K. (1986). Habitat of hydrocarbons at Haltenbanken (PVT-modelling as a predictive tool in hydrocarbon exploration). *Habitat of hydrocarbons on the Norwegian continental shelf*, 259-274.

Hollander, N. B. (1982). Evaluation of the hydrocarbon potential offshore mid Norway. *Oil & Gas Journal, 80*(15), 168-172.

Hollander, N. B. (1984). Geohistory and hydrocarbon evaluation of the Haltenbank area *Petroleum Geology of the North European Margin* (pp. 383-388): Springer.

Hudec, Michael R., & Jackson, Martin P. A. (2007). Terra infirma: Understanding salt tectonics. *Earth-Science Reviews, 82*(1–2), 1-28. doi: http://dx.doi.org/10.1016/j.earscirev.2007.01.001

Jacobsen, W. V., & van Veen, P. (1984). *The Triassic offshore Norway north of 62N*. Norwegian petroleum Society Graham & Trotman.

Koch, J. O., & Heum, O. R. (1995). Exploration trends of the Halten Terrace. *Norwegian Petroleum Society Special Publications, 4*, 235-251.

Marsh, N., Imber, J., Holdsworth, R. E., Brockbank, P., & Ringrose, P. (2010). The structural evolution of the Halten Terrace, offshore Mid- Norway: extensional fault growth and strain localisation in a multi- layer brittle–ductile system. *Basin Research, 22*, 195-214.

Müller, Reidar, Petter Nystuen, Johan, Eide, Frøydis, & Lie, Hege. (2005). Late Permian to Triassic basin infill history and palaeogeography of the Mid-Norwegian shelf—East Greenland region *Norwegian Petroleum Society Special Publications* (Vol. Volume 12, pp. 165-189): Elsevier.

NPD. (2014). Structure elements in the Norwegian Continental Shelf. Retrieved 26.02, 2014, from http://www.npd.no/en/Topics/Geology/Temaartikler/Structure-elements/

NPD, The Norwegian Petroleum Directorate., & OED, Minestry of Petroleum and Energy. (2014). The norwegian Continental Shelf. *Facts 2014 - The Norwegian Petroleum Sector*.

OED, The Minestry of Petroleum and Energy. (2014). APA 2013 - Stron interest in further eploration of the Norwegian shelf [Press release]. Retrieved from http://www.regjeringen.no/en/dep/oed/press-center/press-releases/2014/apa-2013--strong-interest-in-further-exp.html?id=749575

Osmundsen, P. T., & Ebbing, J. (2008). Styles of extension offshore mid- Norway and implications for mechanisms of crustal thinning at passive margins. *Tectonics, 27*.

Osmundsen, P. T., Sommaruga, A., Skilbrei, J. R., & Olesen, O. (2002). Deep structure of the Mid Norway rifted margin. *Norsk Geologisk Tidsskrift, 82*, 205 -224.

Pascoe, R., Hooper, R., Storhaug, K., & Harper, H. (1999). *Evolution of extensional styles at the southern termination of the Nordland Ridge, Mid-Norway: a response to variations in coupling above Triassic salt.* Paper presented at the Geological Society, London, Petroleum Geology Conference series.

Peacock, D. C. P., & Sanderson, D. J. (1994). Geometry and development of relay ramps in normal fault systems. *AAPG bulletin, 78*(2), 147-165.

Price, I., & Rattey, R. P. (1984). Cretaceous tectonics off mid-Norway: implications for the Rockall and Faeroe-Shetland troughs. *Journal of the Geological Society, 141*(6), 985-992.

Richardson, Nick J. , Underhill, John R., & Lewis, Gavin (2005). The role of evaporite mobility in modifying subsidence patterns during normal fault growth and linkage, Halten Terrace, Mid-Norway *Basin Research, 17*, 203-223.

Rønnevik, H. C., Bergsager, E. I., Moe, A., Øvrebø, O., & Navrestad, T. (1975). The geology of the Norwegian continental shelf. *Petroleum and the continental shelf of north-west Europe, 1*, 117-129.

Rønnevik, H.C. (2000). The exploration experience from Midgard to Kristin—Norwegian Sea. *Norwegian Petroleum Society Special Publications, 9*, 113-129.

Schlumberger. (2014). Petrel E&P Software Platform. *Software.* from http://www.software.slb.com/products/platform/Pages/petrel.aspx

Skilbrei, Jan Reidar, & Olesen, Odleiv. (2005). Deep structure of the Mid-Norwegian shelf and onshore-offshore correlations: Insight from potential field data. In J. P. N. E. E. Bjørn T.G Wandås & G. Felix (Eds.), *Norwegian Petroleum Society Special Publications* (Vol. Volume 12, pp. 43-68): Elsevier.

Skogseid, J., Planke, S., Faleide, J. I., Pedersen, T., Eldholm, O., & Neverdal, F. (2000). NE Atlantic continental rifting and volcanic margin formation, in Dynamics of the Norwegian Margin. *The Geological Society, London, Special Publication, 167*, 295-326.

Swiecicki, T., Gibbs, P. B., Farrow, G. E., & Coward, M. P. (1998). A tectonostratigraphic framework for the Mid-Norway region. *Marine and Petroleum Geology, 15*(3), 245-276.

Tsikalas, Filippos, Faleide, Jan Inge, Eldholm, Olav, & Blaich, Olav Antonio. (2012). The NE Atlantic conjugate margins. *Regional Geology and Tectonics: Phanerozoic Passive Margins, Cratonic Basins and Global Tectonic Maps: Phanerozoic Passive Margins, Cratonic Basins and Global Tectonic Maps*, 141.

Twiss, Robert J., & Moores, E. M. (1992). *Structural Geology* (Third ed.): WH Freeman, New York.

Vendeville, B. C., Ge, Hongxing, & Jackson, M. P. A. (1995). Scale models of salt tectonics during basement-involved extension. *Petroleum Geoscience, 1*(2), 179-183.

Wilson, Paul, Elliott, Gavin M., Gawthorpe, Rob L., Jackson, Christopher A. L., Michelsen, Lisa, & Sharp, Ian R. (2013). Geometry and segmentation of an evaporite-detached normal fault array: 3D seismic analysis of the southern Bremstein Fault Complex, offshore mid-Norway. *Journal of Structural Geology, 51*, 74-91.

Withjack, M.O., & Callaway, S. (2000). Active Normal Faulting Beneath a Salt Layer: An Experimental Study of Defomration Patterns in the Cover Sequence. *AAPG bulletin, 84*, 627-651.

Withjack, M.O., Meisling, K.E., & Russell, L.R. (1989). Forced folding and basement-detached normal faulting in the Haltenbanken area, offshore Norway. *Extensional tectonics and stratigraphy of the North Atlantic margins: AAPG Memoir, 46*, 567-575.

Withjack, M.O., Schlische, R.W., & Olsen, P.E. (2002). Rift-basin structure and its influence on sedimentary systems. *Society of Sedimentary Geology (SEPM), 73*, 57-81.

Zalmstra, Heleen. (2013). *Reactivation of the Ringvassøy-Loppa Fault Complex, SW Barents Sea - the role of detachments.* UIO.

Ziegler, Peter A. (1988). Evolution of the arctic-north Atlantic and the western Tethys--a visual presentation of a series of paleogeographic-paleotectonic maps. *Mem.-Am. Assoc. Pet. Geol, 43*, 164-196.